

LONG-BASELINE NEUTRINO OSCILLATIONS

The Global Experimental Program

Lecture 2 of 2

International Neutrino Summer School 2026

Zoya Vallari

zoya@physics.osu.edu

Roadmap - Part II

By the end: where the field stands today, and how the next decade resolves δ_{CP} and the mass ordering.

- Three generations of long-baseline experiments
- The current generation up close: T2K and NOvA
- Combining the two: the NOvA + T2K joint fit
- Adding reactors and atmospheric: breaking degeneracies
- The next generation: Hyper-Kamiokande and DUNE

Learning outcomes

Place the major long-baseline experiments across three generations

Explain how T2K and NOvA extract oscillation parameters

Explain why combining different experiments breaks degeneracies

Contrast the Hyper-K and DUNE strategies and what each resolves

1

Three generations of oscillation experiments

Choosing L and E:

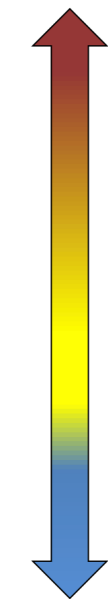
Energy (E)



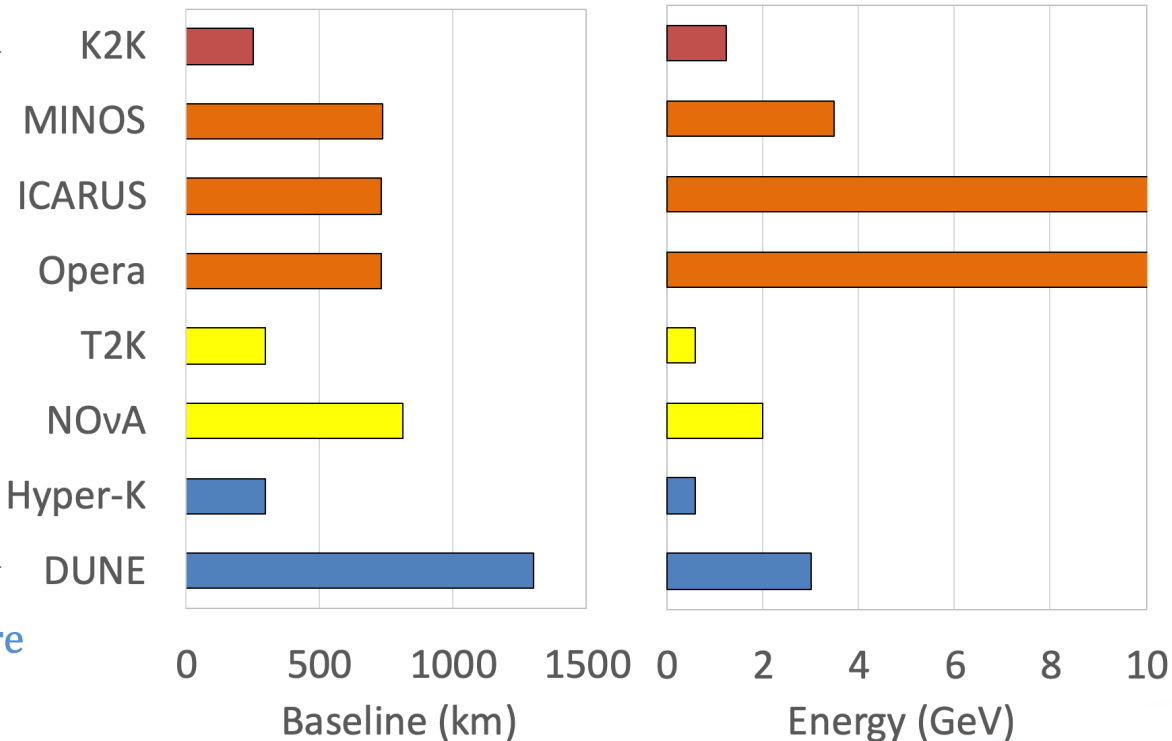
Baseline (L)

Past

Image Credit: Alex Himmel



Future

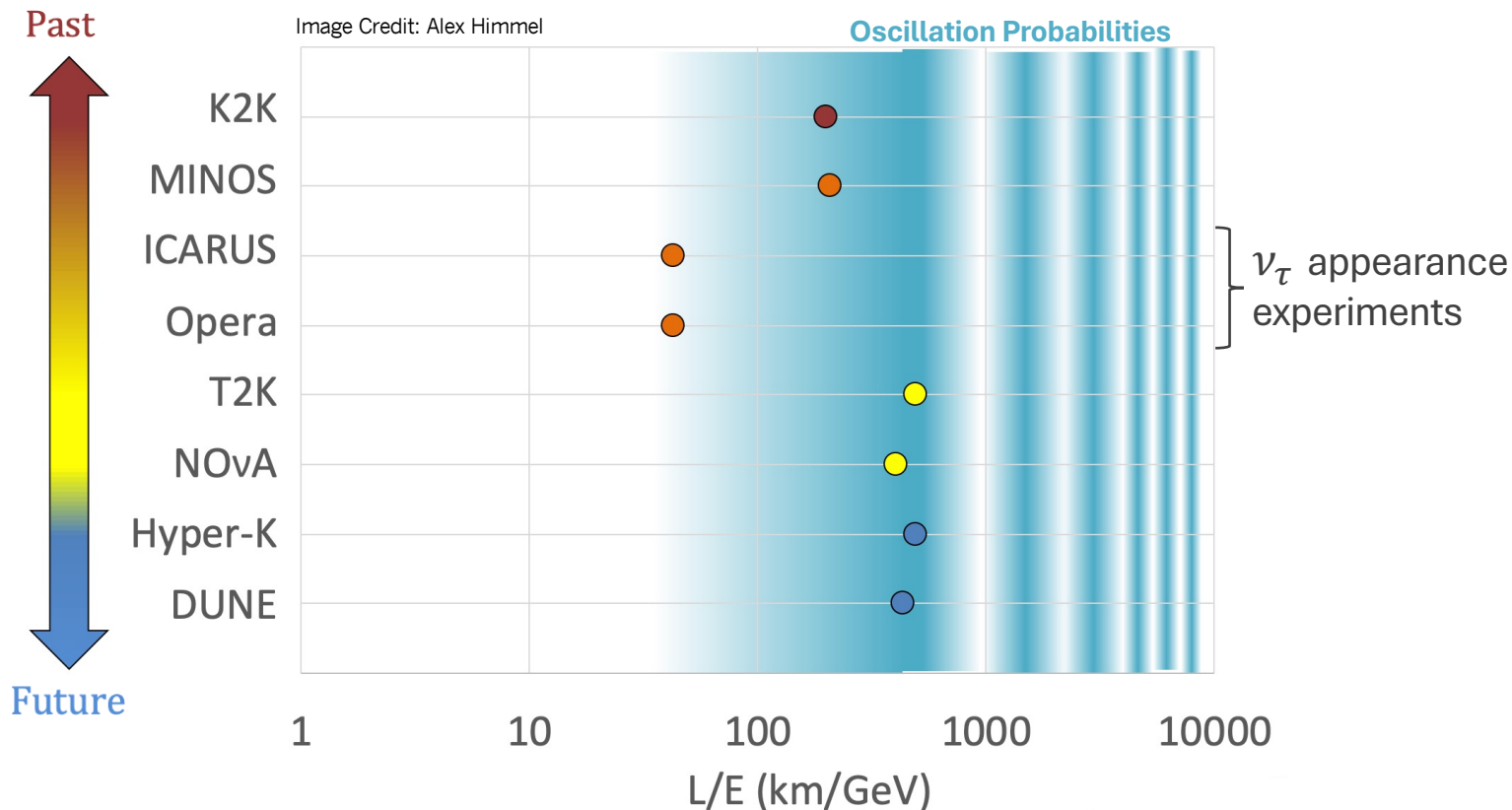


Detector
Technology

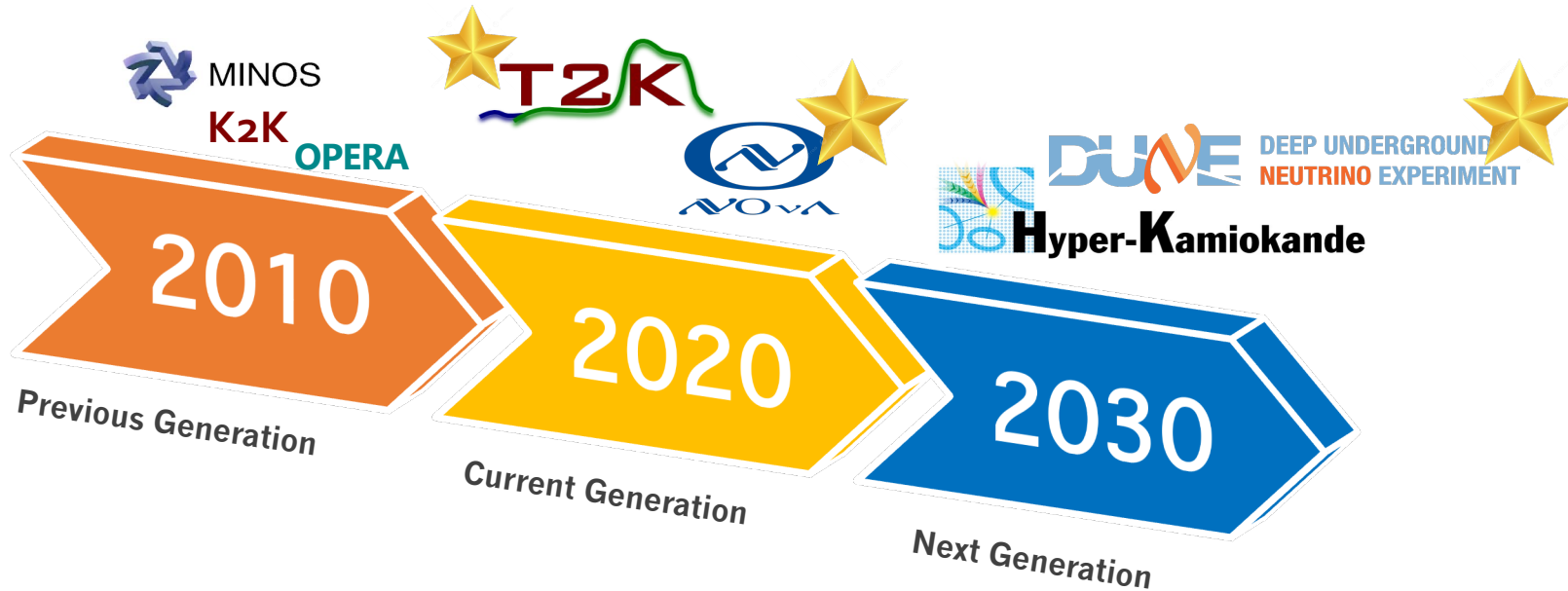
- Must pick all three together.

Choosing L/E:

- Fix L/E at the first oscillation maximum
- Longer L $\rightarrow$ higher E at the maximum



3 Generations of long-baseline experiments



Experiments I am (or have been) a part of

Contemporary & Future Generations

Adapted from [annurev-nucl-102020-101615](#)

	Location	Beam	Baseline
T2K	Japan (Tokai to Kamioka)	J-PARC 500 kW (Upgrade to 1.3 MW)	295 km
NOvA	United States (Fermilab to Ash River, Minnesota)	NuMI 850 kW	810 km
Hyper-K	Japan (Tokai to Kamioka)	J-PARC 1.3 MW	295 km
DUNE	United States (Fermilab to Lead, South Dakota)	LBNF 2 – 2.4 MW tunable	1285 km

Review:

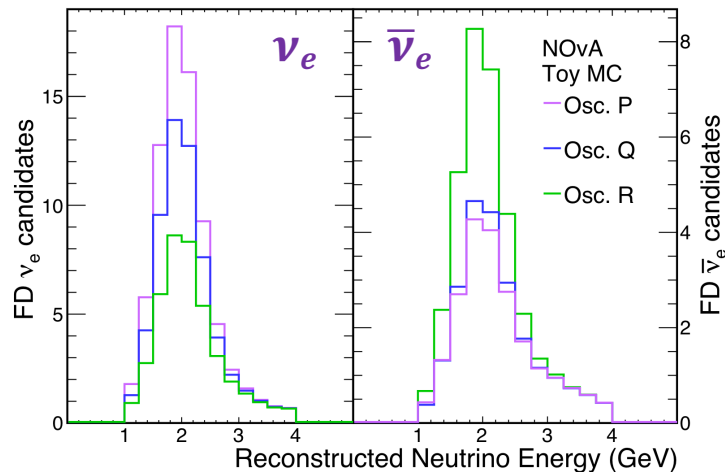
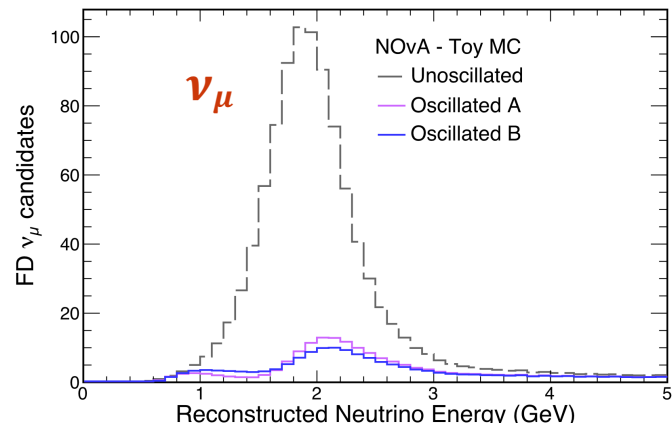
Measuring Oscillations

Measurement

1. **Detect** neutrino interactions.
2. **Tag** the flavor.
3. **Reconstruct** energy.

Inference

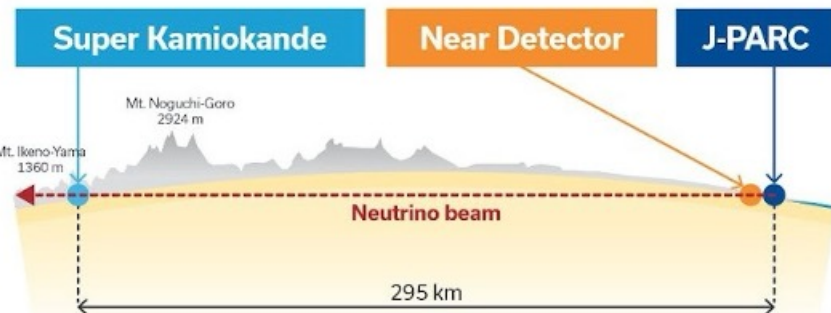
1. Compare with the no oscillation prediction.
2. Compare ν_e and $\bar{\nu}_e$ appearance rate.



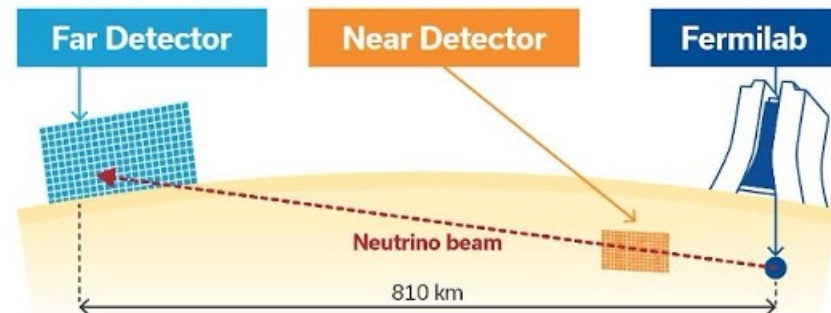
2

The current generation: T2K & NOvA

Japan

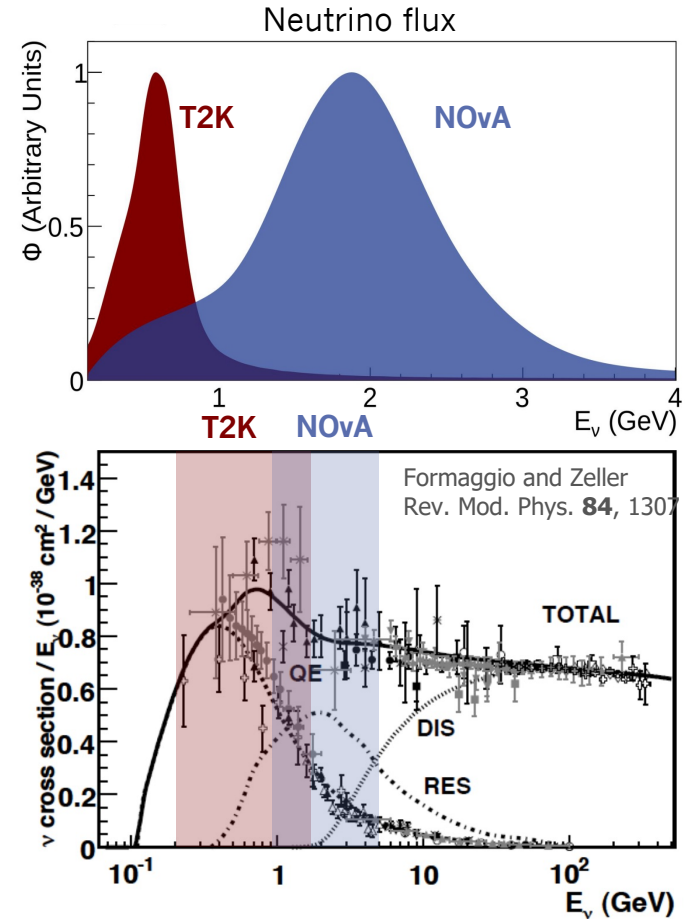


United States



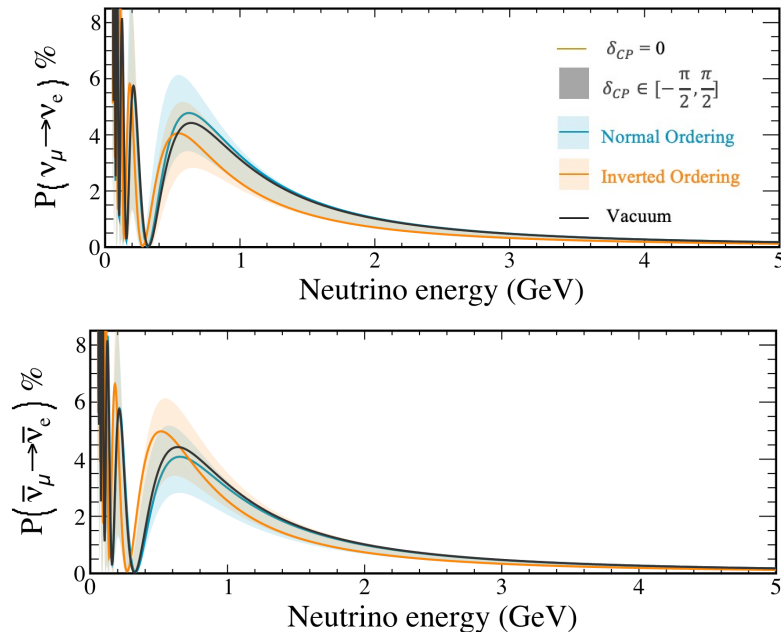
Beamlines (E)

- Both experiments are located off-axis to receive a narrow-band, highly pure muon (anti-)neutrino beam.
 - T2K**: beam from J-PARC, peaks at **0.6 GeV** neutrino energy.
 - NOvA**: beam peaks at **2 GeV** and is delivered from **Fermilab's NuMI**.
- The **difference in neutrino beam energy** leads to qualitatively **different neutrino interactions**
 - T2K**: primarily Quasi-Elastic and 2p2h interactions
 - NOvA**: mix of Quasi-Elastic, 2p2h, Resonant and DIS interactions

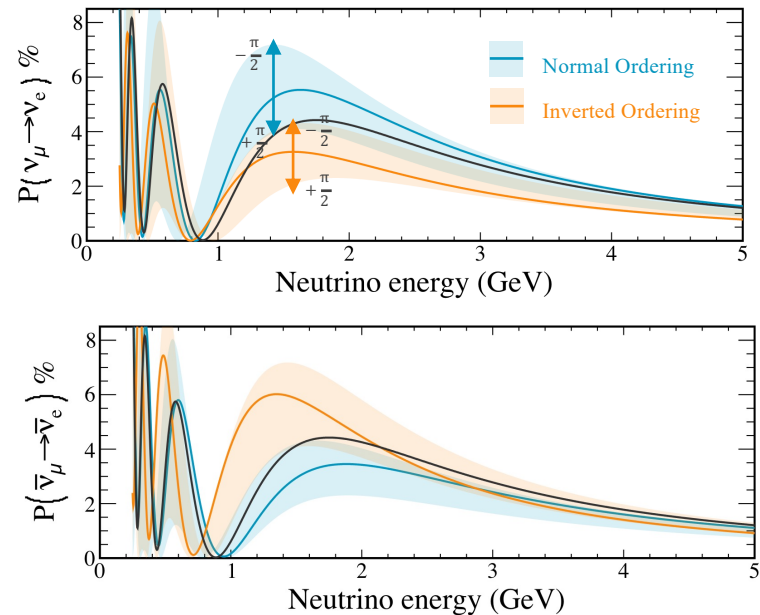


Baselines (L) and Beamlines (E):

T2K: L = 295km



NOvA: L = 810 km

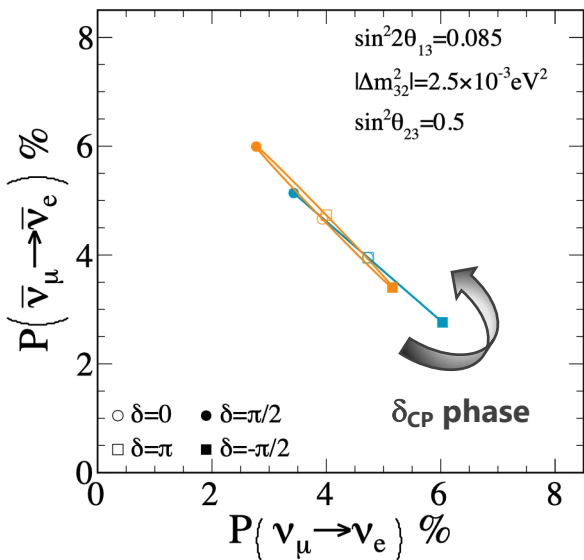


- **NOvA sees larger matter effect** due to higher neutrino energy and longer baseline → **higher sensitivity to mass ordering.**

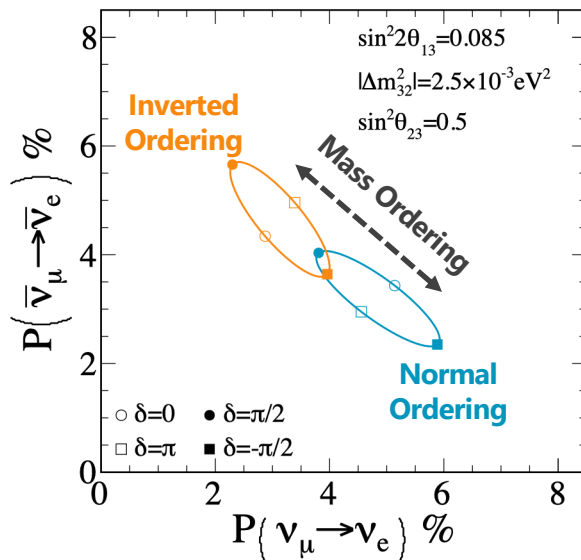
NOvA-T2K Complementarity

- **T2K** measurements isolate impact of **CP violation** while **NOvA** has significant **sensitivity to mass ordering**.

T2K: L = 295km, E = 0.6GeV



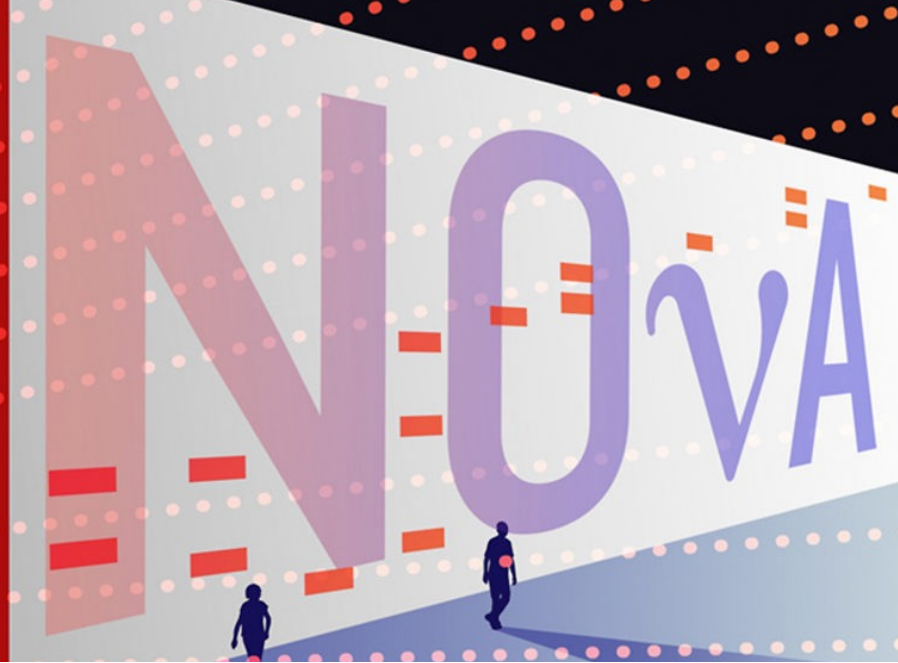
NOvA: L= 810 km, E = 2.0 GeV



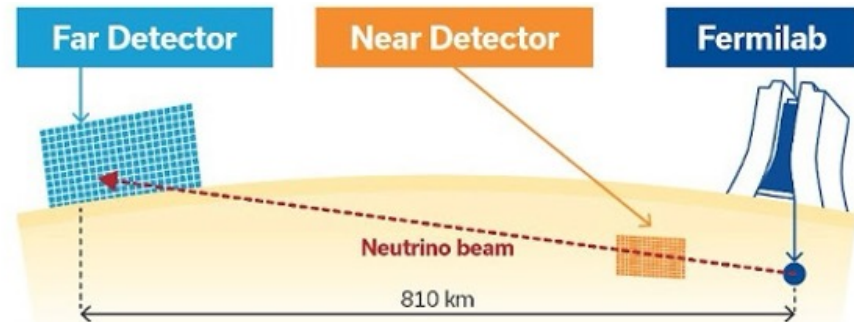
	T2K	NOvA
L (baseline)	295 km	810 km
Energy (beam peak)	0.6 GeV	2 GeV
Matter effect*	$\sim \pm 9\%$	$\sim \pm 19\%$
CP effect*	$\sim \pm 30\%$	$\sim \pm 25\%$

*calculated at beam peak energy

MEASURING OSCILLATIONS with



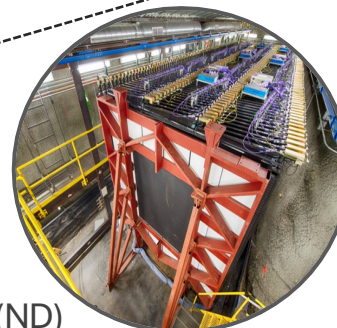
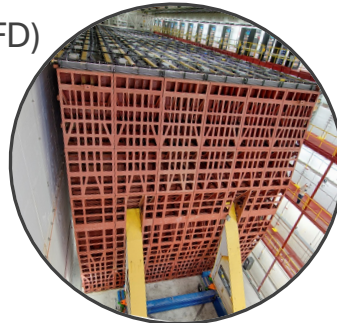
1. **Detect** neutrino interactions.
2. **Tag** the flavor.
3. **Reconstruct** energy.



NOvA Detectors

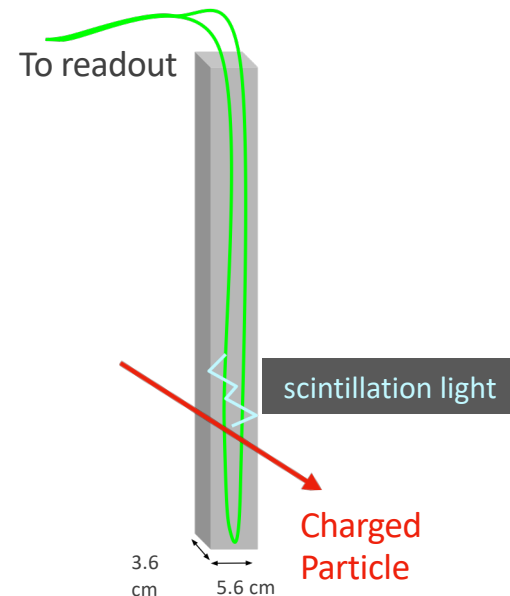


Far Detector (FD)
14 kT, on the
surface

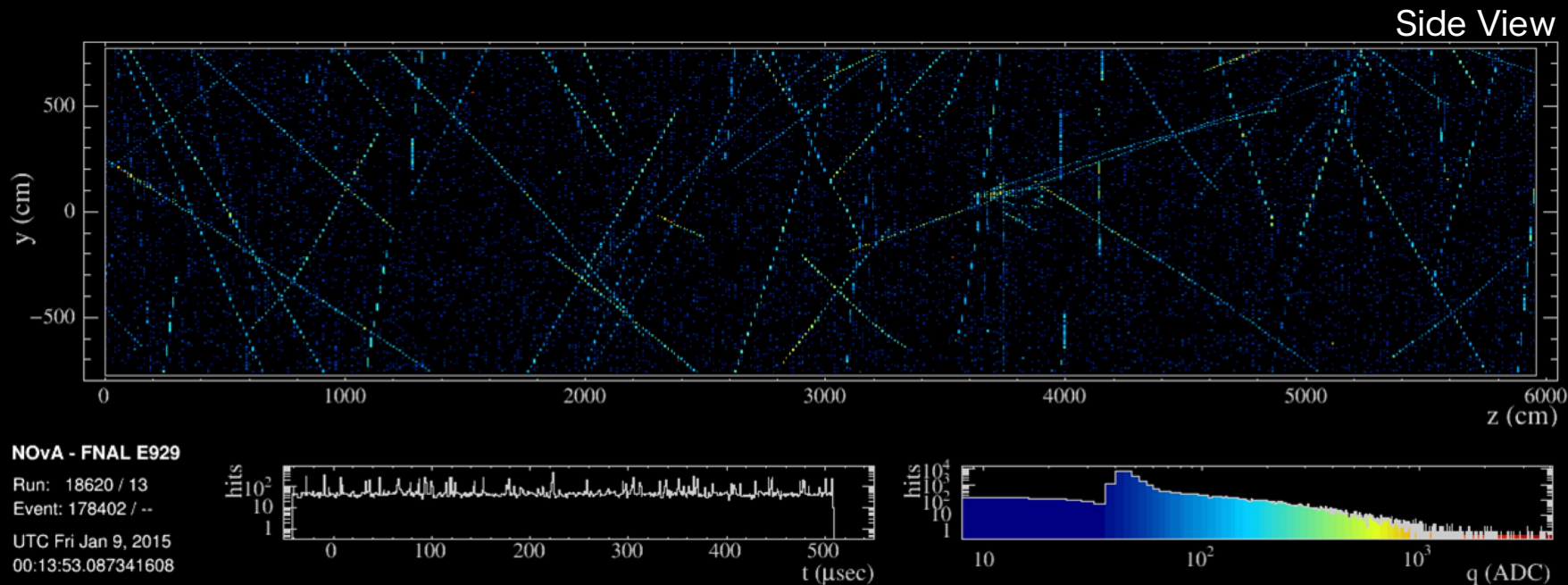


Near Detector (ND)
300 T, underground

ND and FD are
functionally identical
**segmented liquid
scintillator detectors.**

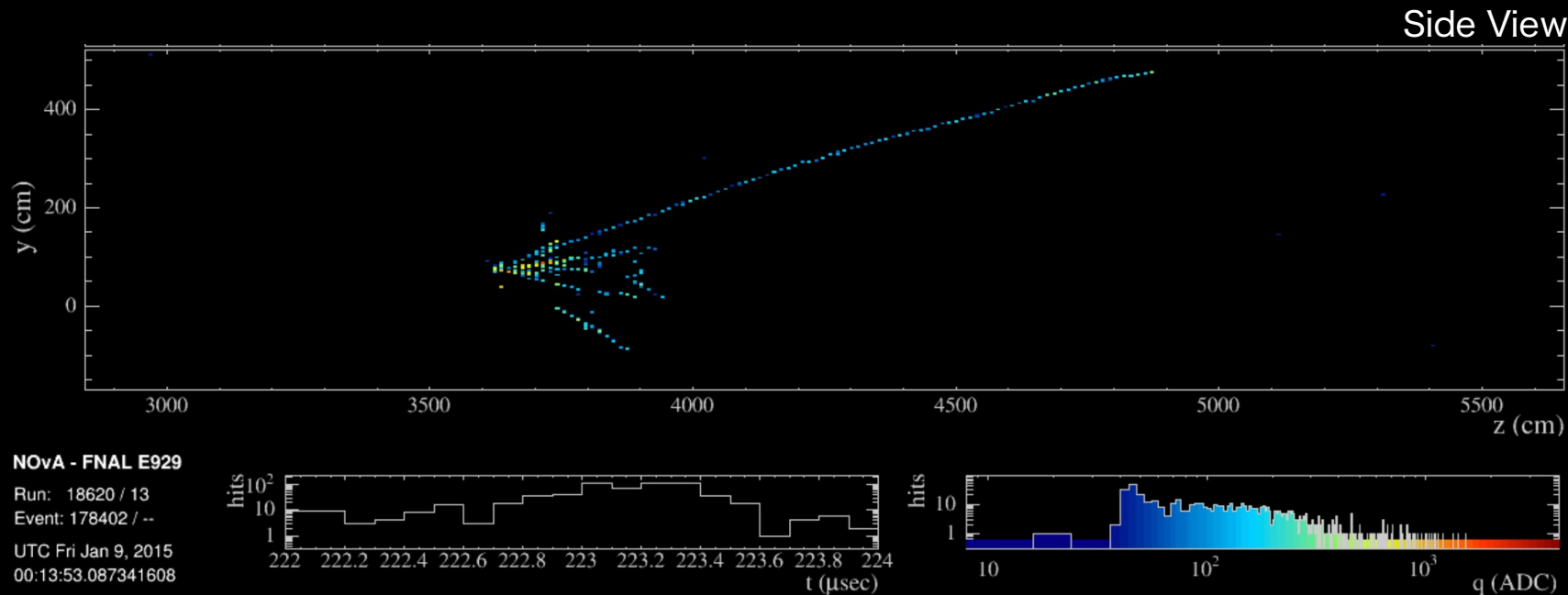


NOvA Detectors



- ~150 kHz of cosmic rays at the FD which is on the surface.

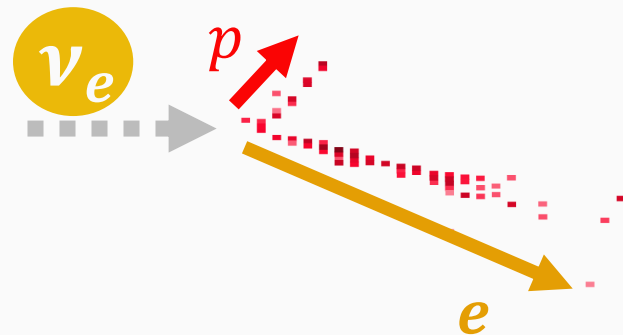
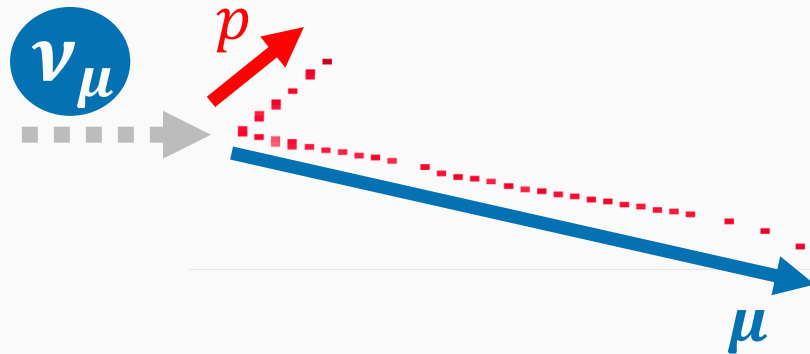
NOvA Detectors



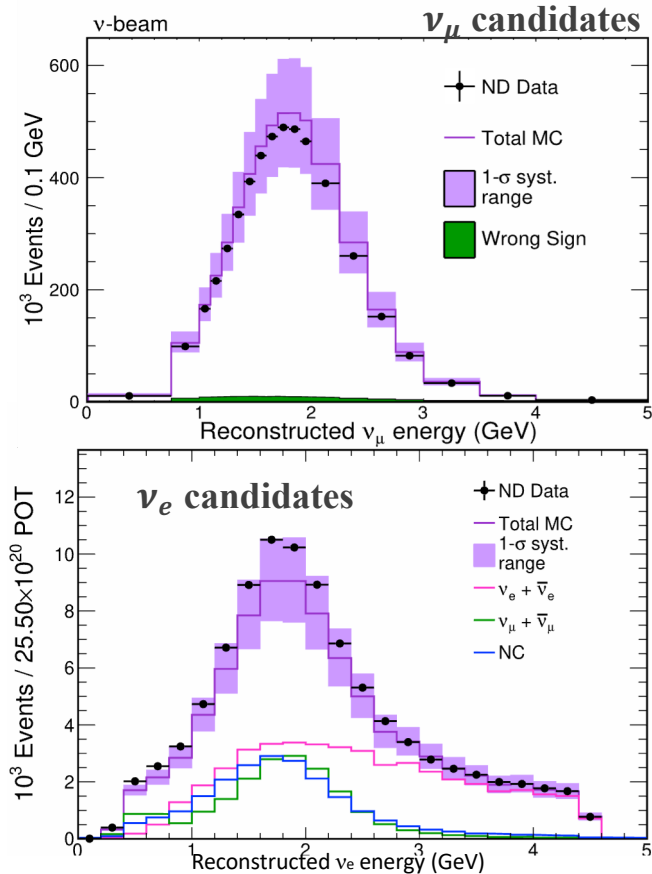
- Good spatial resolution ($\sim$ few cm) and timing resolution ($\sim 10\text{ns}$) allows to isolate neutrino interaction from 99% of cosmic backgrounds.

Tag Flavors & Reconstruct Energy

- Optimized for EM showers.
 - ~6 samples per radiation length (~40 cm) making **muon-electron** identification easy.
- Neutrino candidates are identified using a **convolutional neural network (CNN)**.
- Energy is reconstructed via **tracking (muon)** and **calorimetry (electromagnetic, hadronic)**.



NOvA ND Data

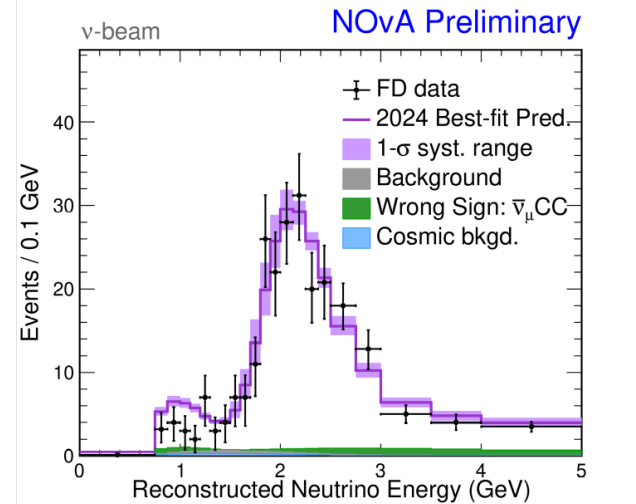


- Exceptional statistics at the ND leads to negligible statistical uncertainty.
 - **~6.5M ν_μ (~1.5M)** candidate events
 - Use this sample to predict both ν_μ and ν_e at the FD
 - **~100k ν_e** candidate events
 - Background intrinsic beam ν_e prediction at the FD.

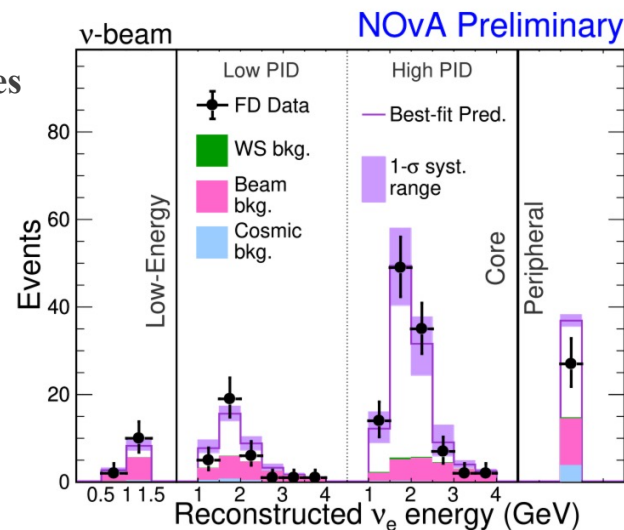
NOvA FD Data:

- Observed **384 ν_μ** and **106 $\bar{\nu}_\mu$** candidates
 - In the absence of oscillations, we'd expect ~ 2100 and ~ 500 .
- We observe **181 ν_e** and **32 $\bar{\nu}_e$** appearance candidates.
 - The predicted backgrounds are 62 and 12 respectively.

ν_μ candidates

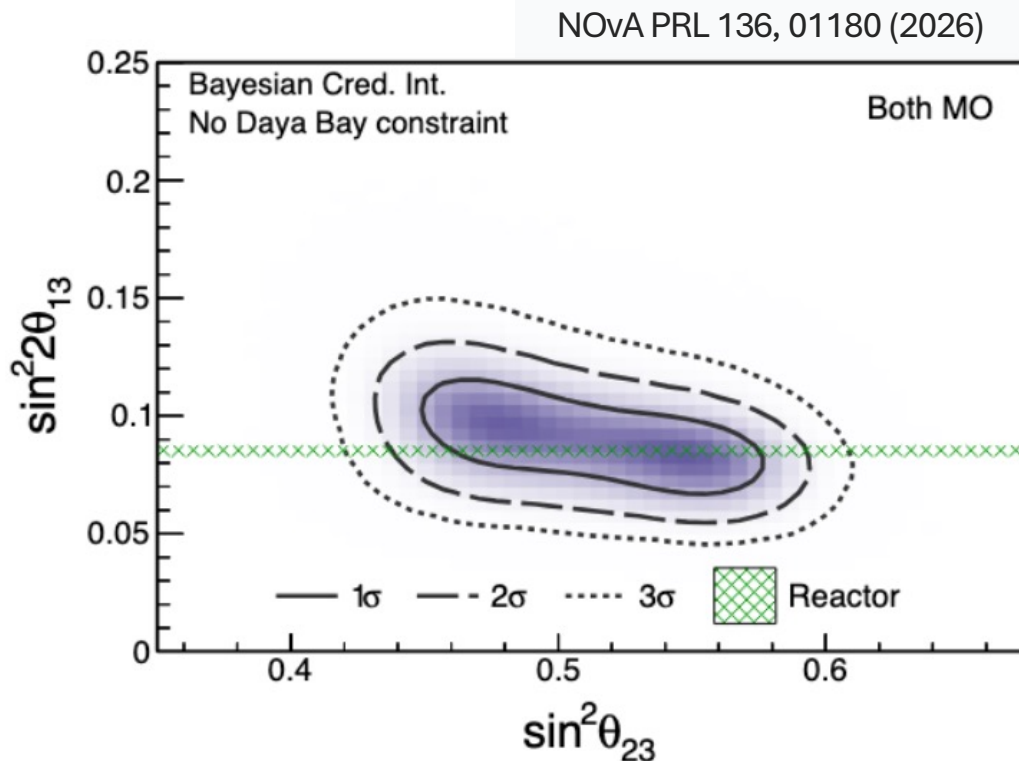


ν_e candidates



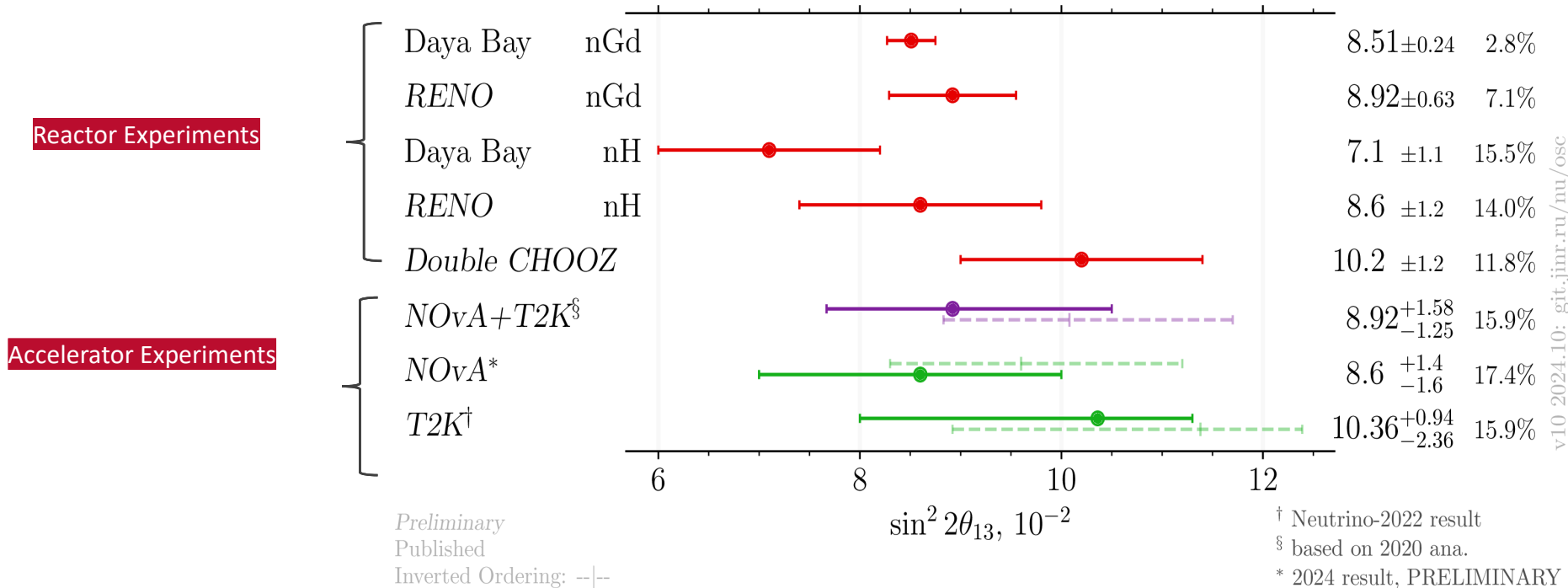
NOvA Results: θ_{13} vs θ_{23}

- Accelerator experiments have a degeneracy between the measurement of mixing angles $\sin^2 2\theta_{13}$ and $\sin^2 \theta_{23}$
- Reactor experiments provide a highly precise measurement of θ_{13} using distinct oscillation channels.



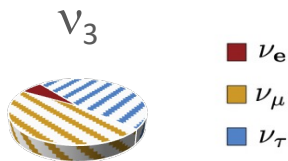
θ_{13}

- Consistent measurements of θ_{13} across reactor and accelerator experiments, provides evidence of the robustness of the PMNS framework of neutrino mixing.



NOvA Results: Δm_{32}^2 and θ_{23}

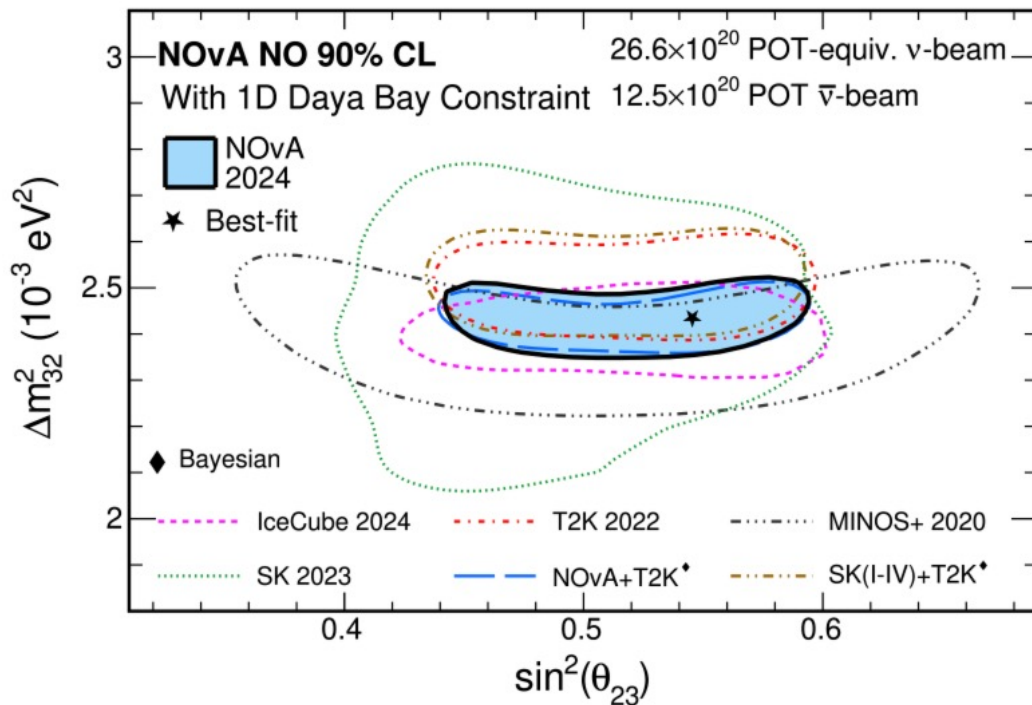
- Global consistency across accelerator, atmospheric and joint-fit results.
- All data is **consistent with maximal mixing** ($\theta_{23} = 45^\circ$) hypothesis.



If $\theta_{23} = 45^\circ \rightarrow |\mathbf{U}_{\mu 3}| = |\mathbf{U}_{\tau 3}|$

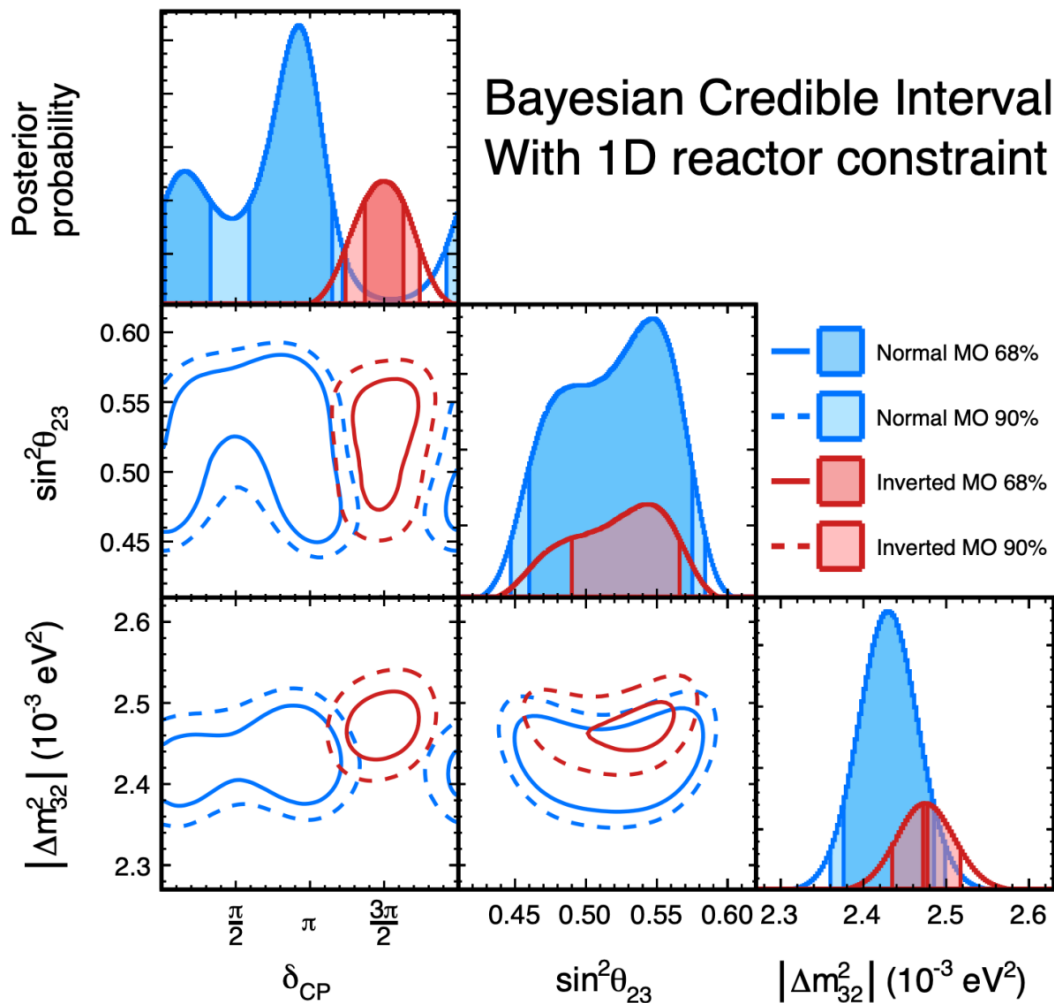
Note: Accelerator experiments use θ_{13} constraint from reactor experiments

NOvA Preliminary

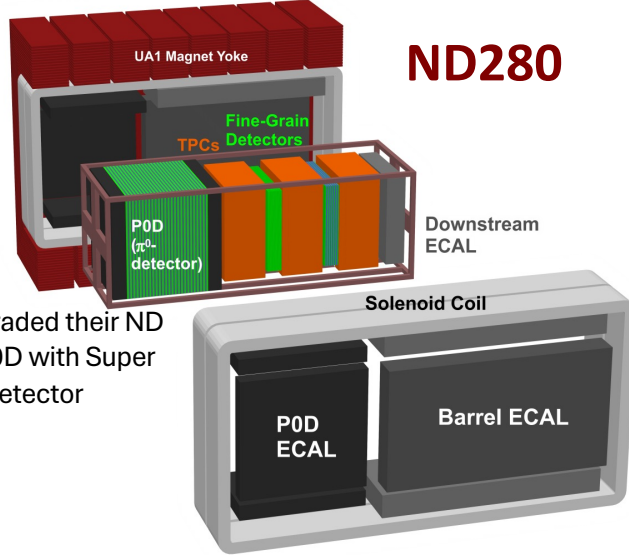


NOvA Results:

- Data is consistent with maximal mixing ($\theta_{23} = 45^\circ$) hypothesis.
- Very precise single experiment measurement of Δm_{32}^2 with 1.5% precision.
- NOvA data show a preference for **NO** (77% posterior):**IO** (23% posterior)
- Bayes factor of 3.3 for NO/IO (77/23). NO ~ 3.3 x more likely than IO.

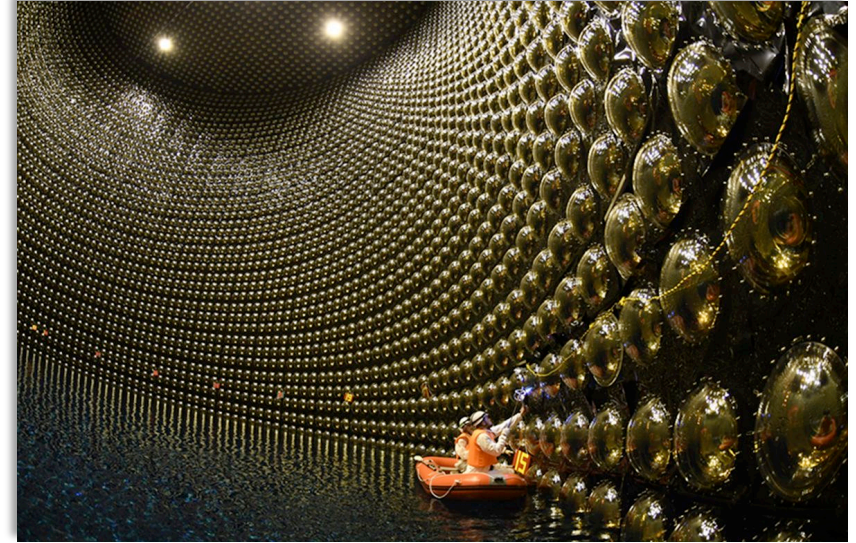


T2K Detectors



T2K has upgraded their ND to replace P0D with Super Fine-Grain Detector

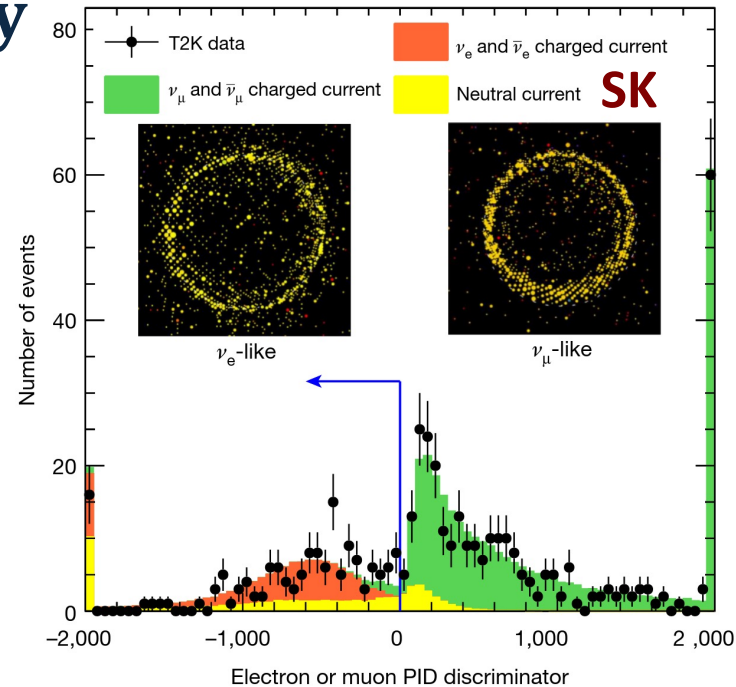
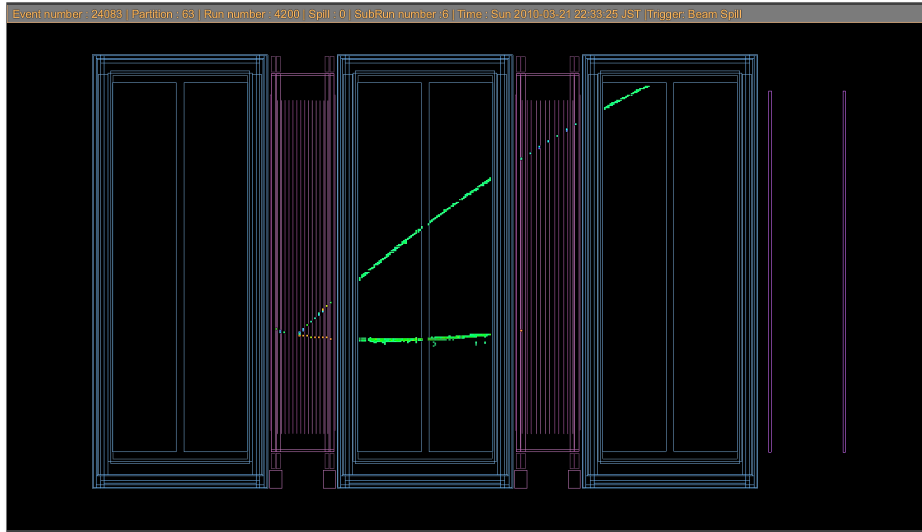
T2K's FD: Super Kamiokande (SK)



- T2K employs **different detector technologies** for Near and Far detectors.
 - ND comprises a set of magnetized detectors employing **particle tracking with plastic scintillator** as the target material.
 - FD is the **50 kt Water Cherenkov Super Kamiokande** detector.

Tag Flavors & Reconstruct Energy

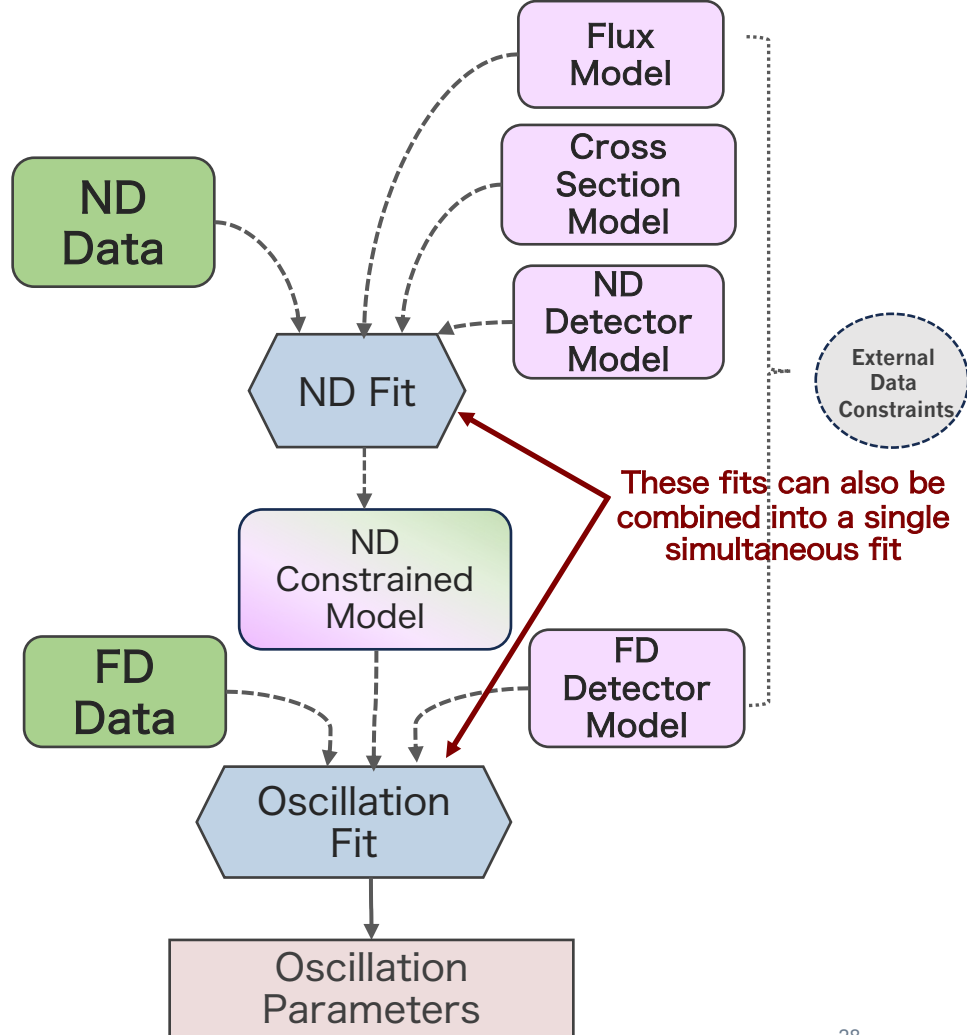
ND280



- Energy of the incoming neutrino is **reconstructed from the lepton kinematics**.
 - ND: Selection based on reconstructed muon track and number of pions - CC1μ0π, CC1μ1π, CC1μNπ
 - FD: Particles are identified by their Cherenkov rings and selections use exclusive topologies.

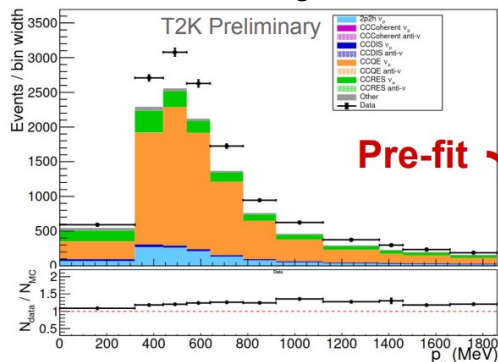
T2K Analysis Strategy

- NOvA and T2K experiments have different analysis approaches driven by contrasting detector designs.
- T2K has a distinct ND from FD so utilizes the constrained model to transfer the ND data constraints.

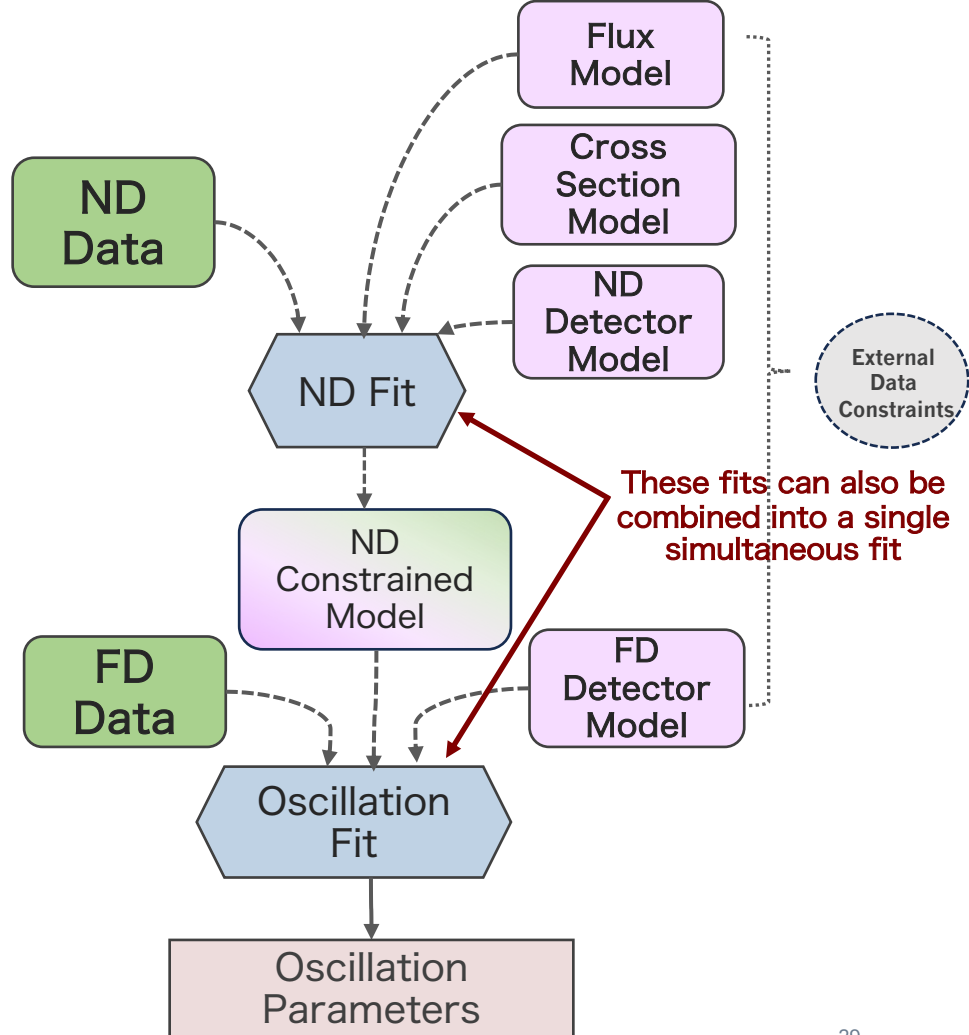
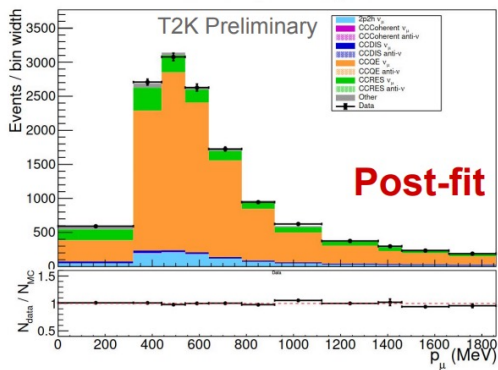


T2K Analysis Strategy

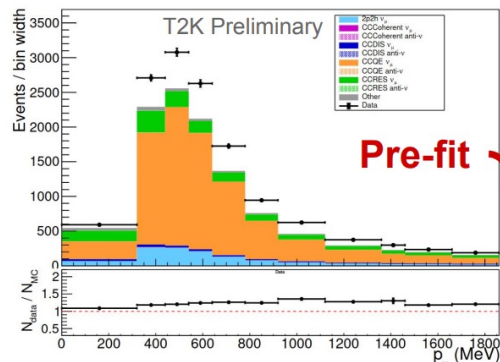
S. King, Neutrino 2026



ND280 FGD1 Fwd ν_μ CC $0\pi 0p$

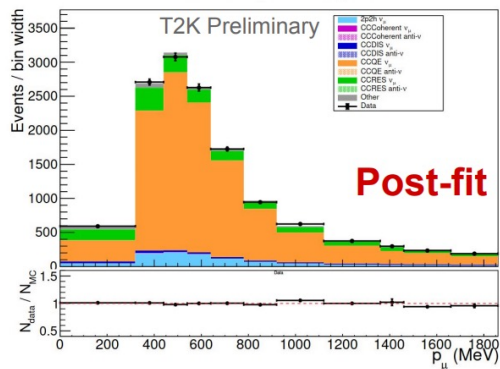


T2K Analysis Strategy

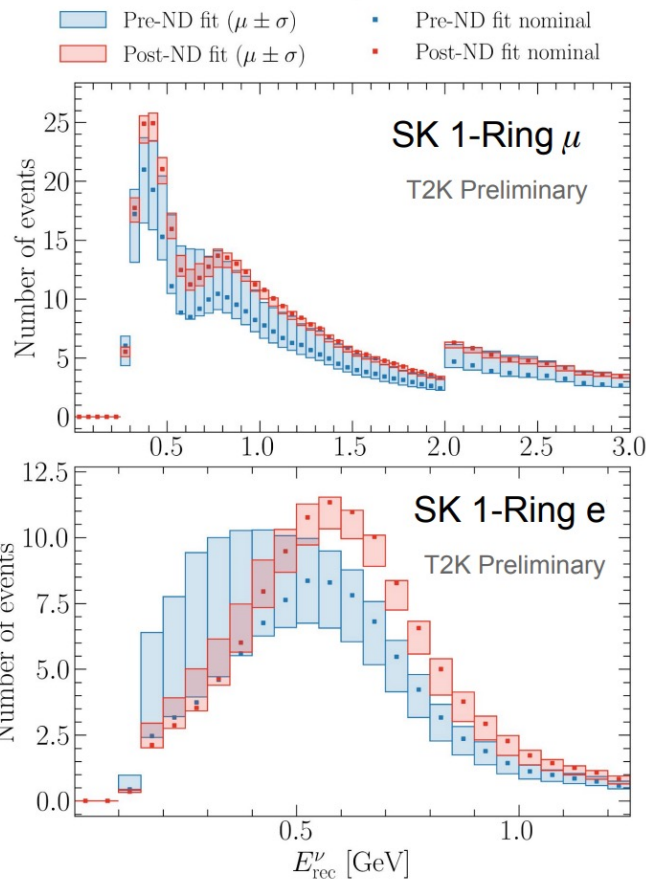


Pre-fit

ND280 FGD1 Fwd ν_{μ} CC 0 π 0p



Post-fit



S. King, Neutrino 2026

**The ND280 fit
reduces the error
on the number of
events selected
at SK**

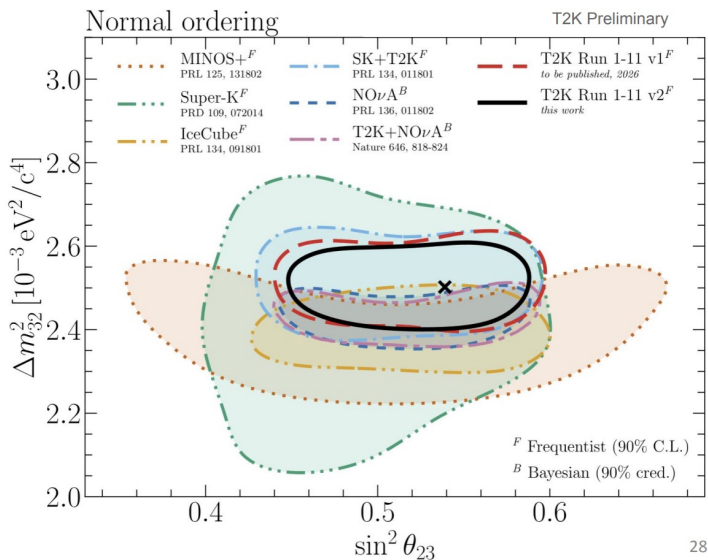
1-Ring μ

19.2 % $\rightarrow$ 3.7 %

1-Ring e

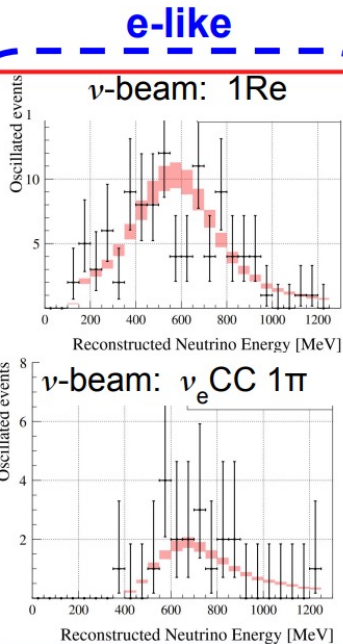
20.3 % $\rightarrow$ 5.7 %

T2K FD Data:

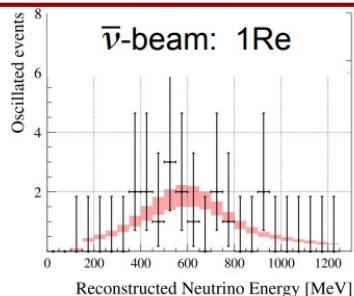


- New results consistent with the old measurements with enhanced precision due to improvement in interaction modeling.

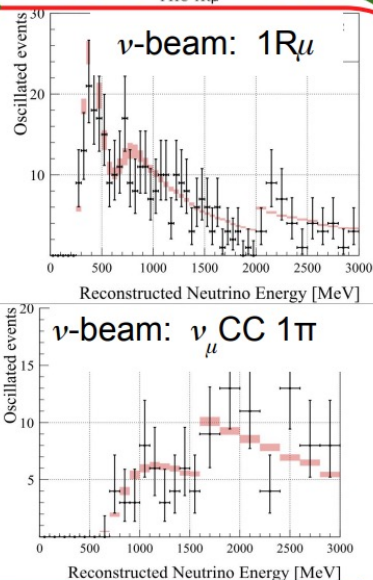
ν -mode



$\bar{\nu}$ -mode



μ -like

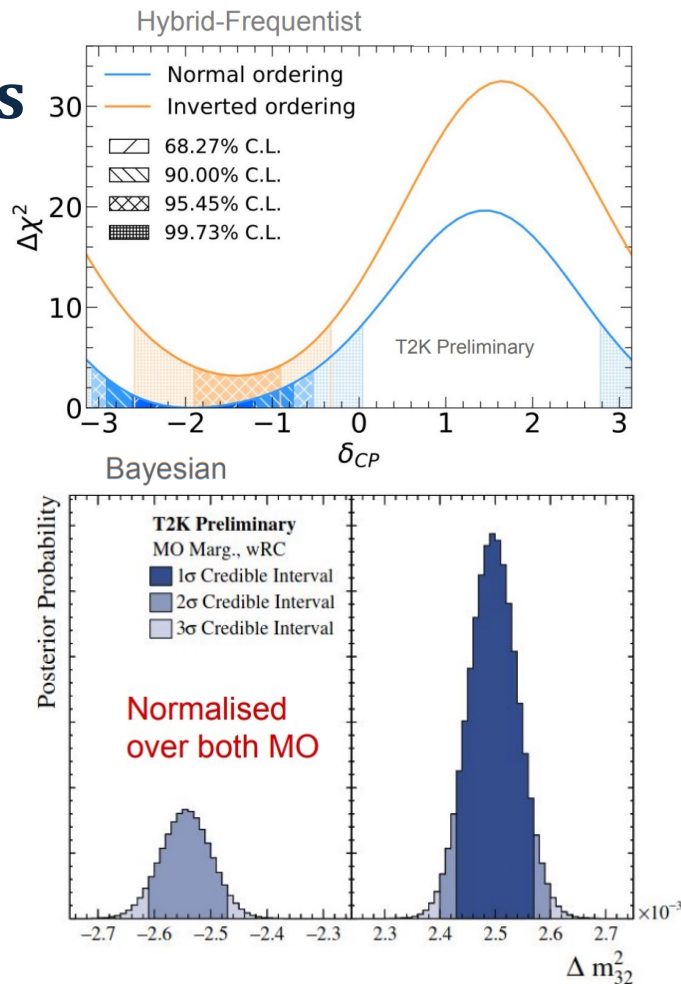


T2K Preliminary

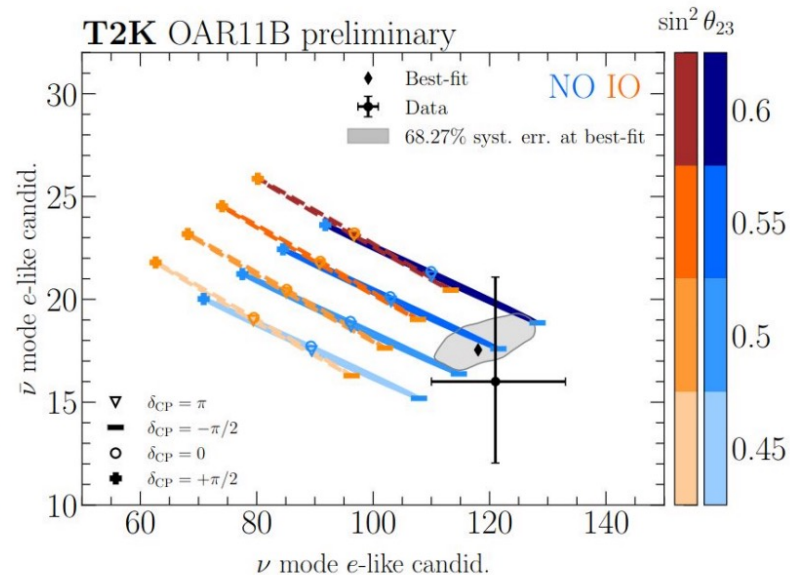
T2K Preliminary

T2K Results

- Preference for maximally CP-violating values.
- CP-conservation excluded at the 95% C.L.
- Weak preference for NO at 78% posterior probability



- High asymmetry observed in ν_e vs $\bar{\nu}_e$ appearance in T2K.



3

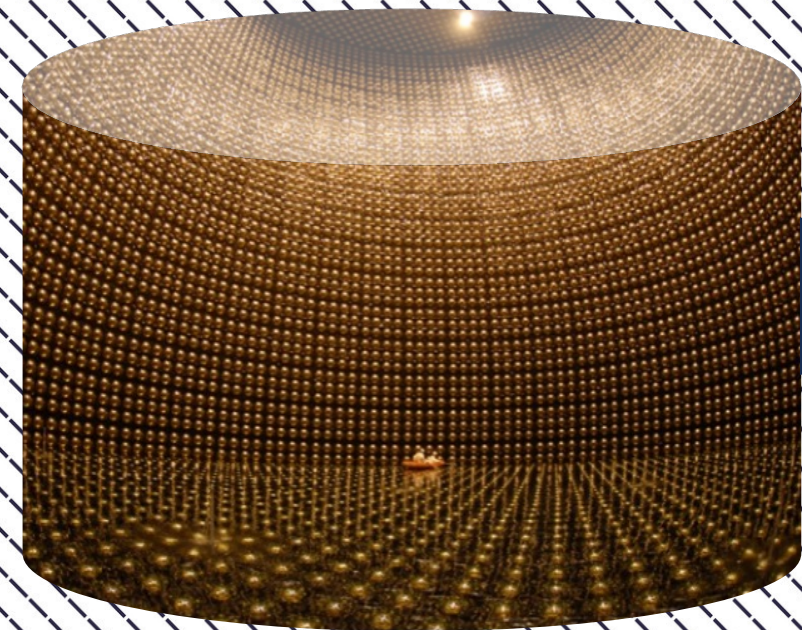
Breaking degeneracies – the joint fits



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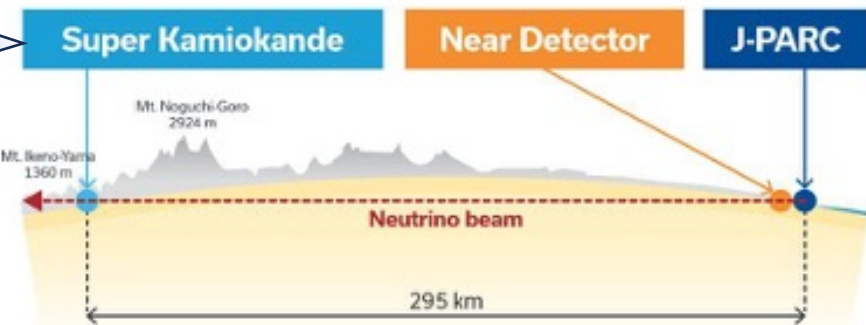
Atmospheric Neutrinos



Beam
Neutrinos

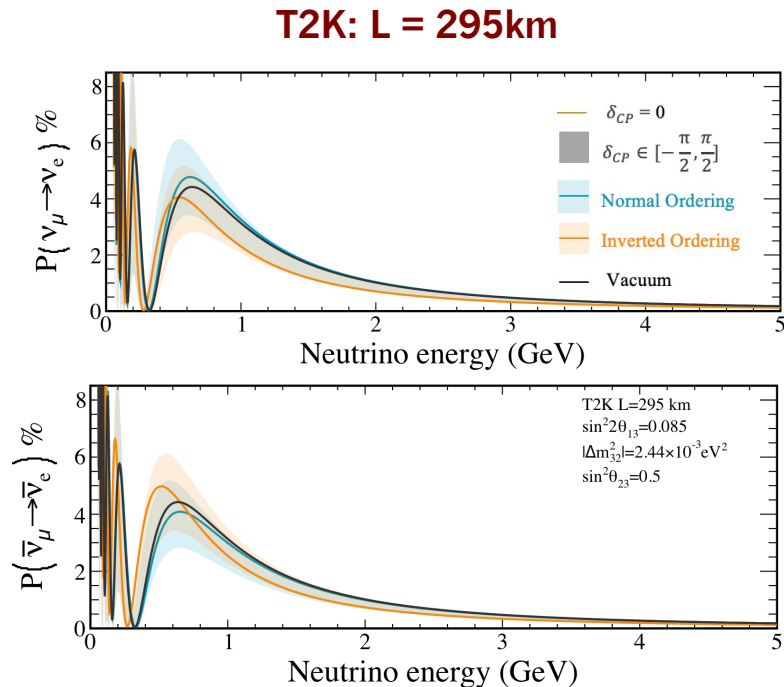
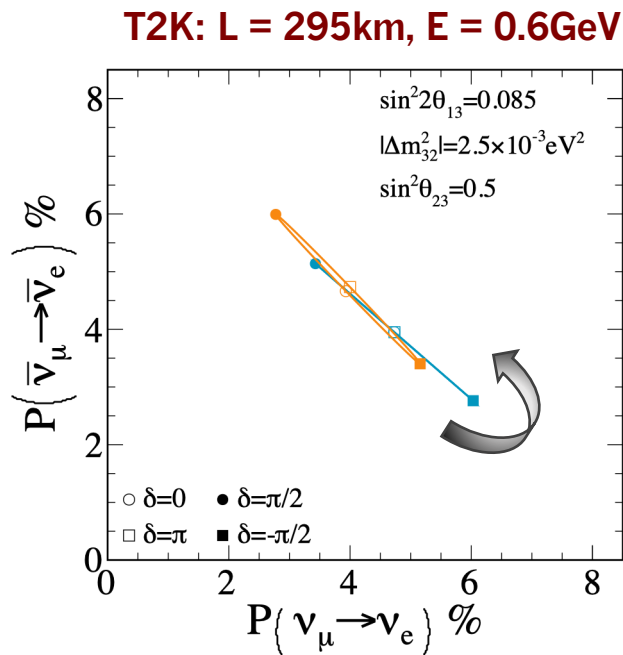
T2K

Japan



T2K

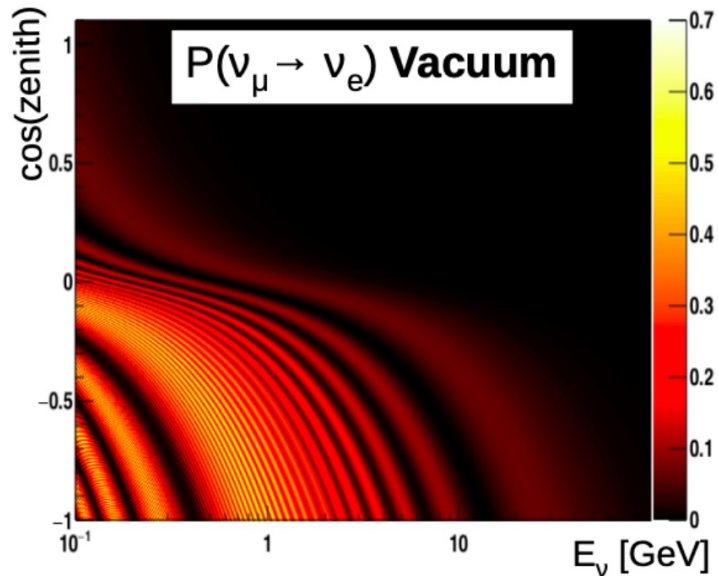
- With a 295 km baseline and a beam energy peaking at 0.6 GeV, T2K sees **minimal matter effect and therefore has limited sensitivity to mass ordering**. Any asymmetry observed in ν_e vs. $\bar{\nu}_e$ appearance can be attributed to CP violation.



- The atmospheric neutrinos at SK travel through the earth at various angles and experience strong matter effect in the few GeV region, which is not degenerate with δ_{CP} .

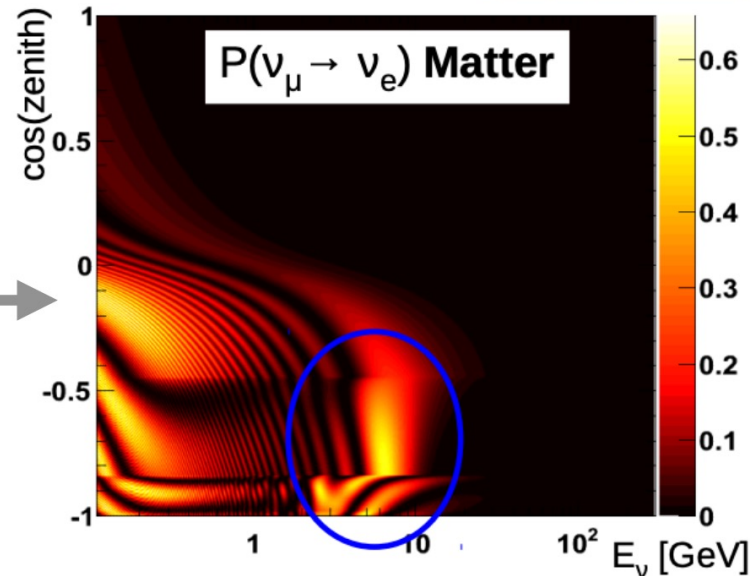
Atmospheric neutrino oscillation probability (normal ordering)

from [C. Bronner @ PANE 2018](#)

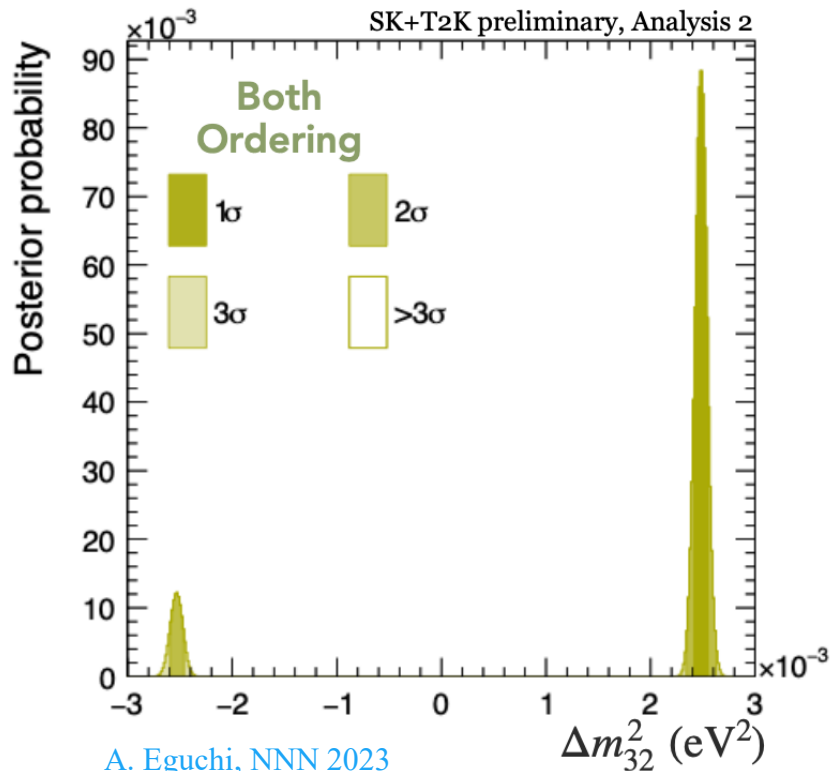


The resonance appears only for ν in NO and $\bar{\nu}$ in IO

► Sensitivity to mass ordering

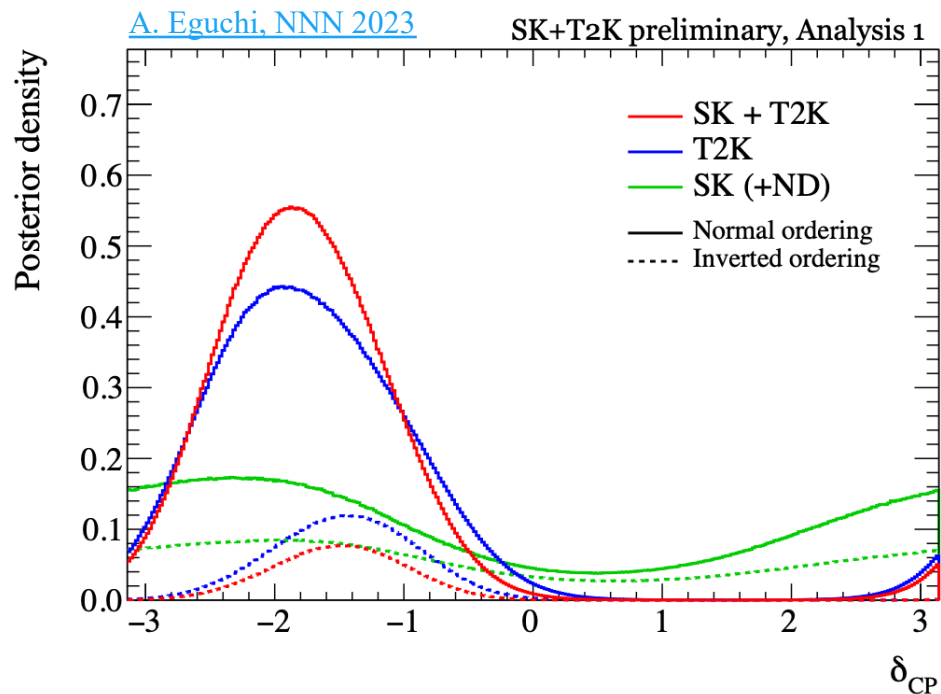
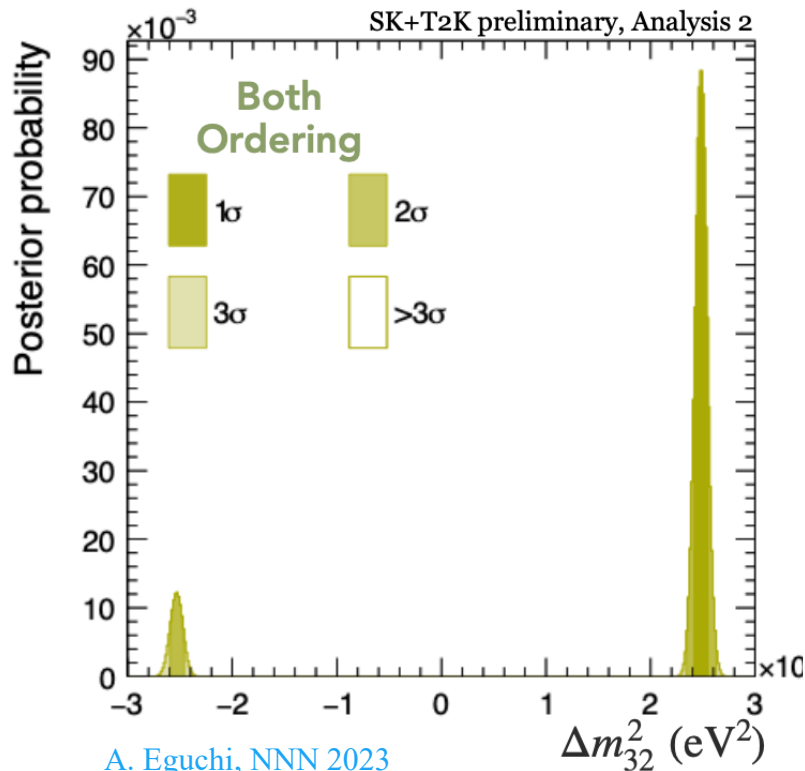


SK + T2K



- Joint analysis shows moderate preference for **Normal Ordering** (~90% posterior) as compared to ~78% posterior for T2K-only fit.

SK + T2K



- A $\sim 2\sigma$ exclusion of CP conserving values of δ_{CP} , irrespective of the ordering.



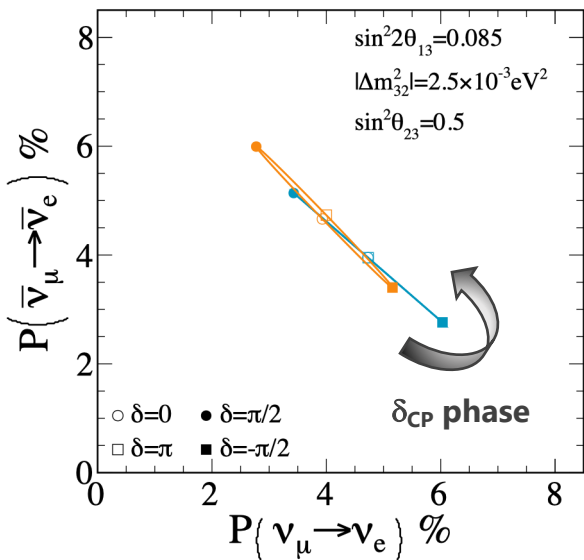
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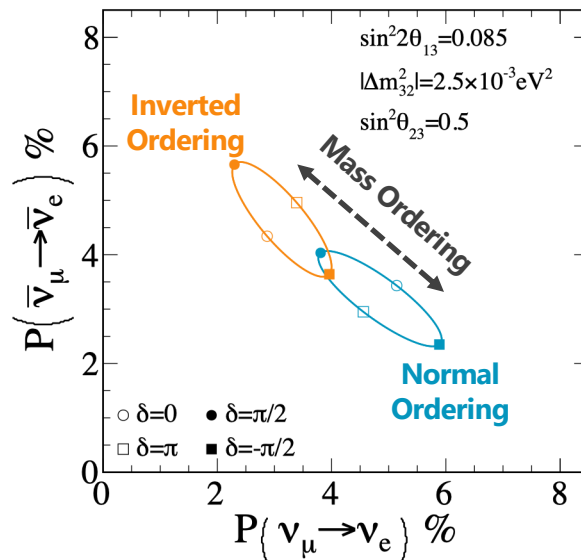
Resolving Degeneracies

- **T2K** measurements isolate impact of **CP violation** while **NOvA** has significant **sensitivity to mass ordering**.
- Joint analysis probes both spaces lifting degeneracies of individual experiments.

T2K: L = 295km, E = 0.6GeV



NOvA: L= 810 km, E = 2.0 GeV



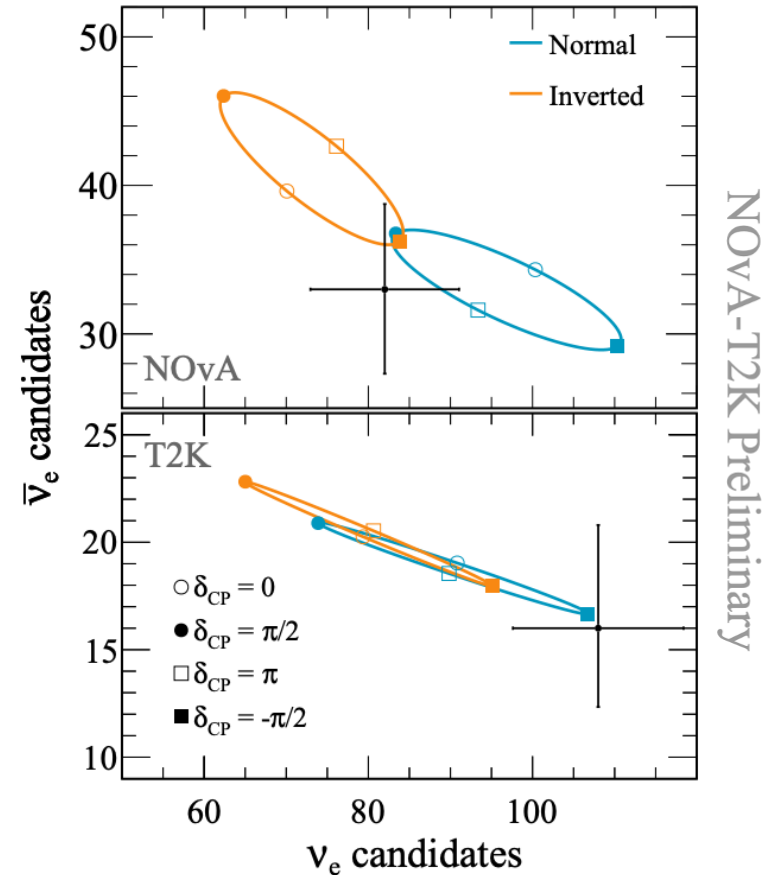
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Matter effect*	$\sim \pm 9\%$	$\sim \pm 19\%$
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*calculated at beam peak energy

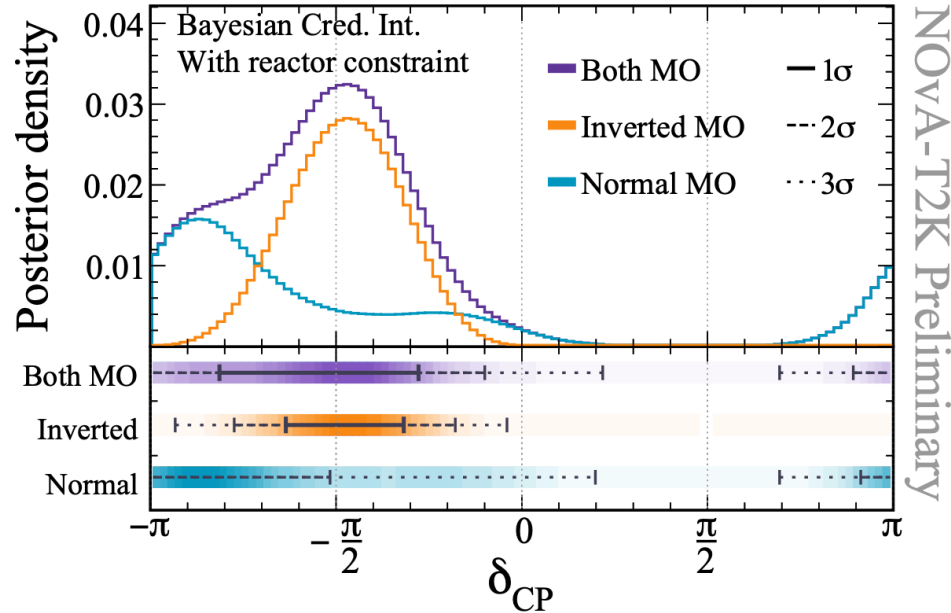
NOvA + T2K Joint Dataset

The joint-fit used **2020-era data** collected by each experiment. Using both experiments data roughly doubles the total statistics at the far detectors.

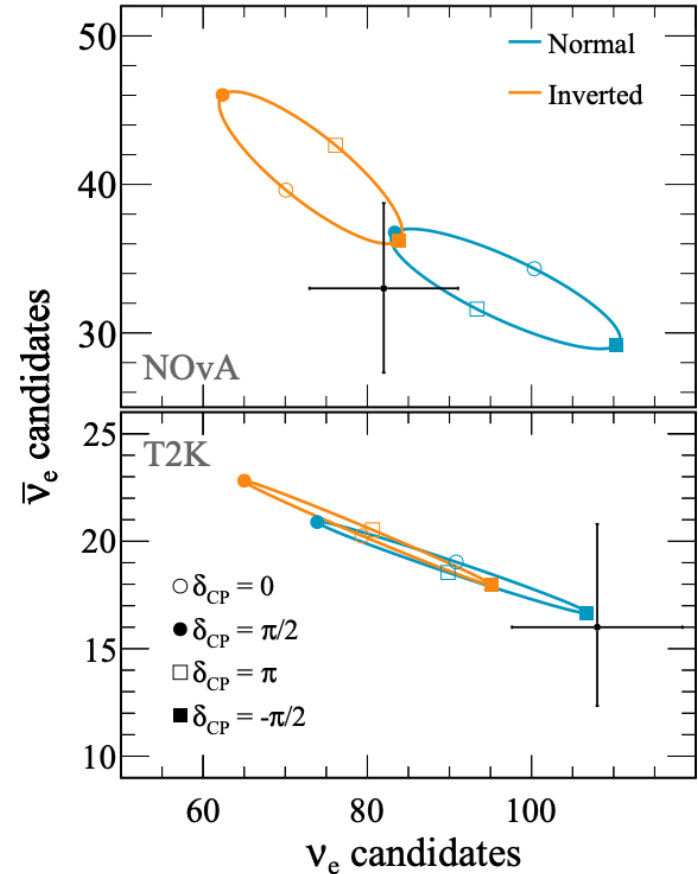
Channel	NOvA	T2K
ν_e	82	94 (ν_e) 14 ($\nu_e 1\pi$)
$\bar{\nu}_e$	33	16
ν_μ	211	318
$\bar{\nu}_\mu$	105	137



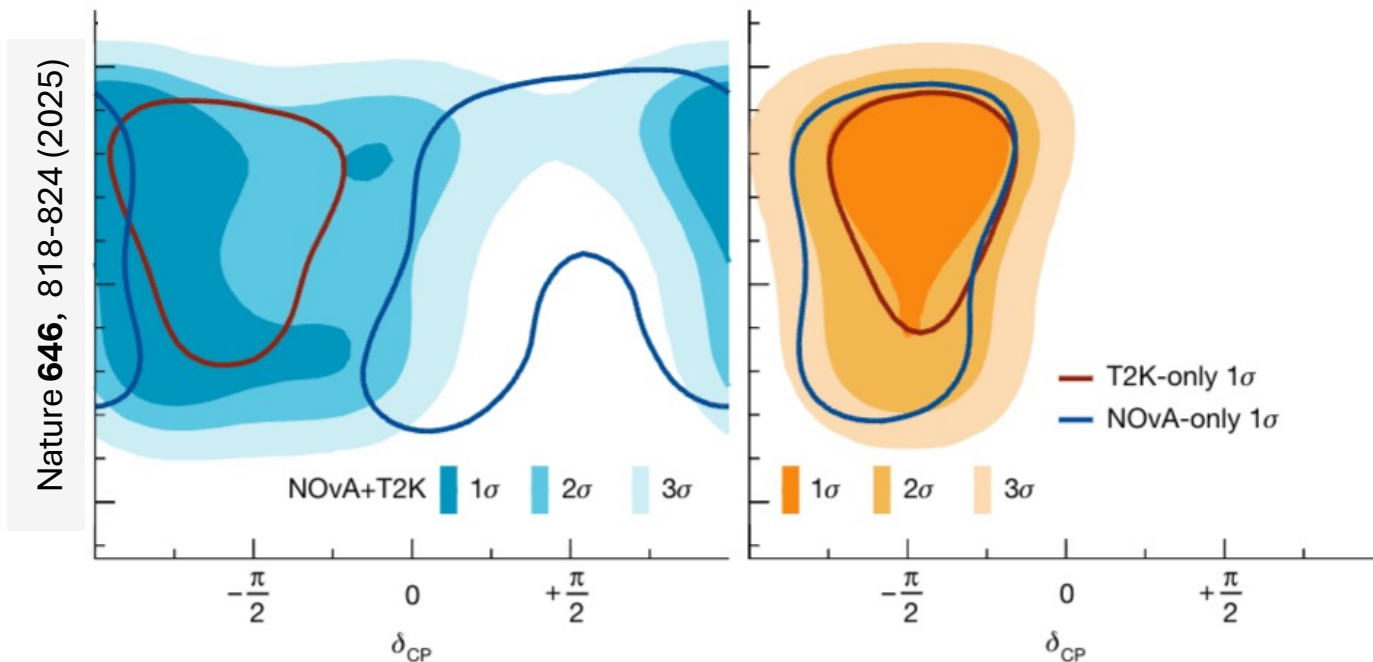
NOvA + T2K Joint Results



- If the **ordering is inverted**, CP conserving values of δ_{CP} ($0, \pi$) lie **outside the 3-sigma** credible interval.



NOvA, T2K, NOvA+T2K

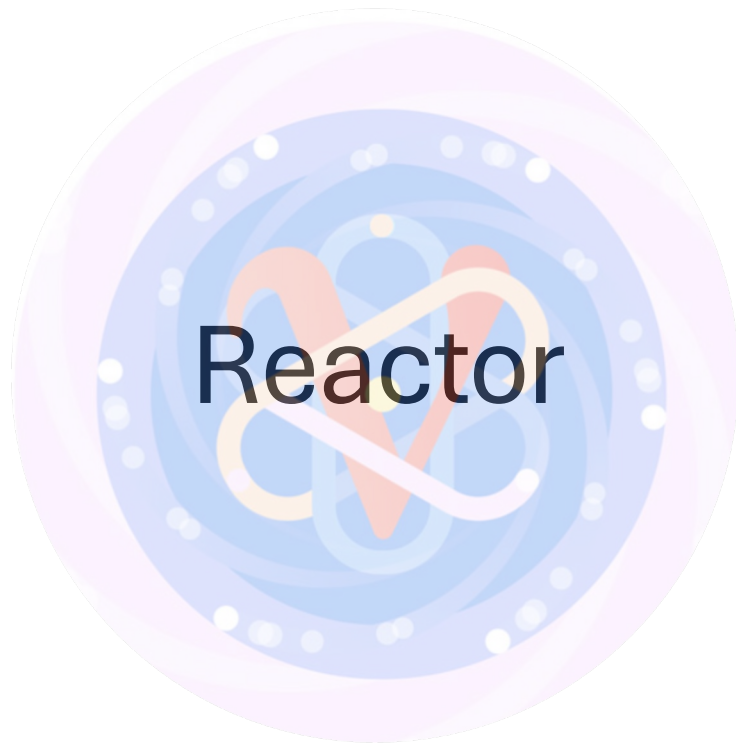


- **NOvA+T2K joint fit weakly prefers IO** (58% posterior in IO, Bayes factor 1.3), driven by overlap in δ_{CP} space.
- Even across different baselines **MO** and δ_{CP} remain degenerate.



Accelerator

+

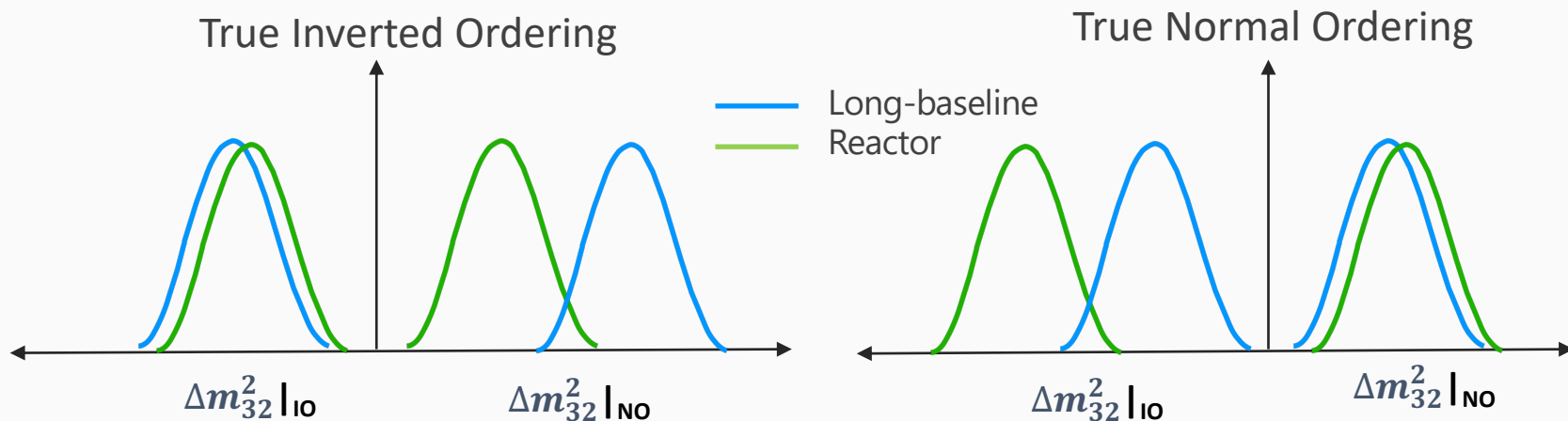


Reactor

Synergies for measuring Mass Ordering

- Precision in Δm_{32}^2 measurements presents an orthogonal lever to measure MO*:
 - Under wrong mass ordering assumption, reactor and long-baseline measurements of Δm_{32}^2 will disagree.

Conceptual Sketch (not to scale)

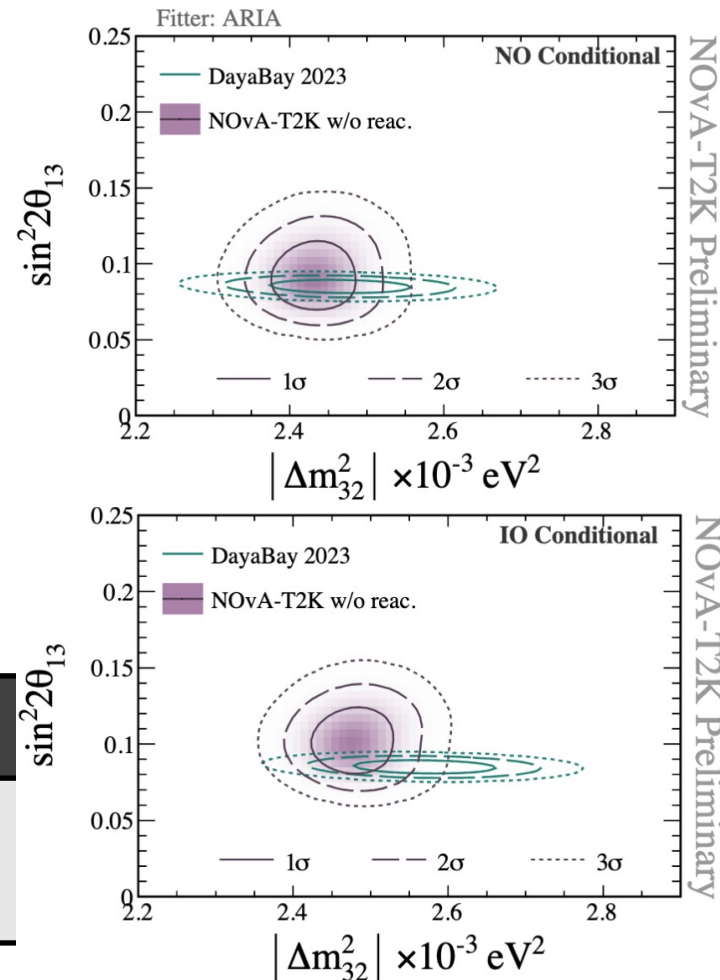


*Nunokawa, Parke and Funchal, PRD 72, 013009 (2005);
Parke and Funchal, PRD 111, 013008 (2025)

NOvA+T2K+Daya Bay

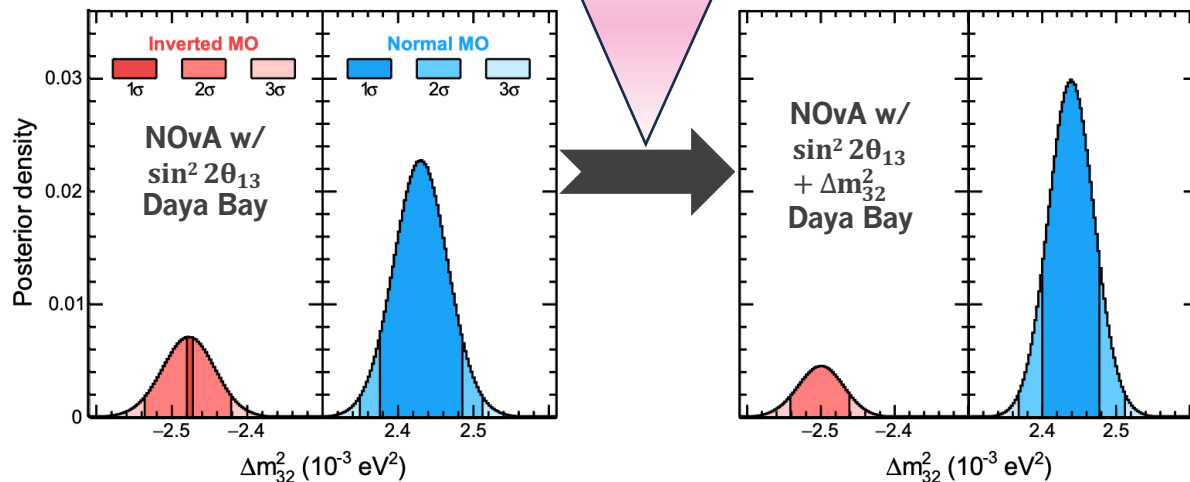
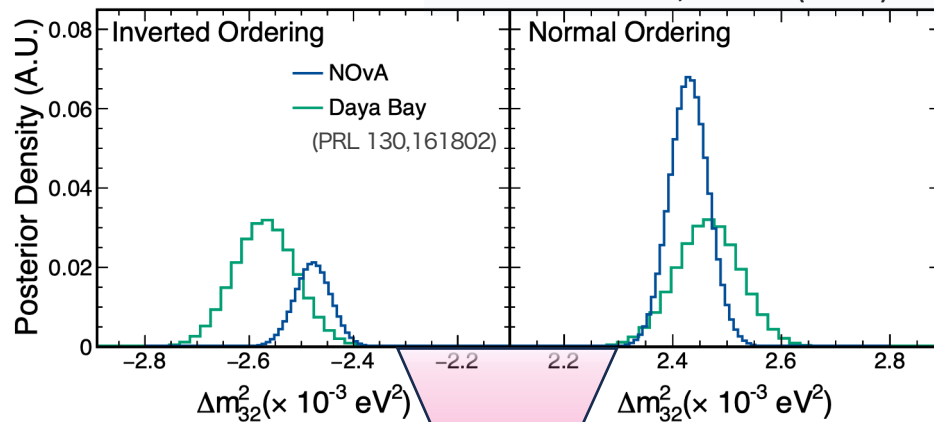
- Including the Δm_{32}^2 constraint from the Daya Bay, reverse the mass ordering preference back to the Normal Ordering.
- No significant preference for either mass ordering in the joint analysis.**

	NOvA - T2K w/o reactor	NOvA - T2K - 1D Daya Bay	NOvA - T2K - 2D Daya Bay
Bayes factor	2.47 Inverted/Normal ~71% : ~29% posterior	1.34 Inverted/Normal ~58% : ~43% posterior	1.44 Normal/Inverted ~59% : ~41% posterior



NOvA + Daya Bay

- Including Δm_{32}^2 from reactor experiments enhances mass ordering significance.
- Driven by precision in Δm_{32}^2 measurement.



External Constraints

Bayes Factor
(Normal/Inverted)

NOvA w/
 $\sin^2 2\theta_{13}$
Daya Bay

3.3

77% / 23%
Posterior density

NOvA w/
 $\sin^2 2\theta_{13} + \Delta m_{32}^2$
Daya Bay

6.6

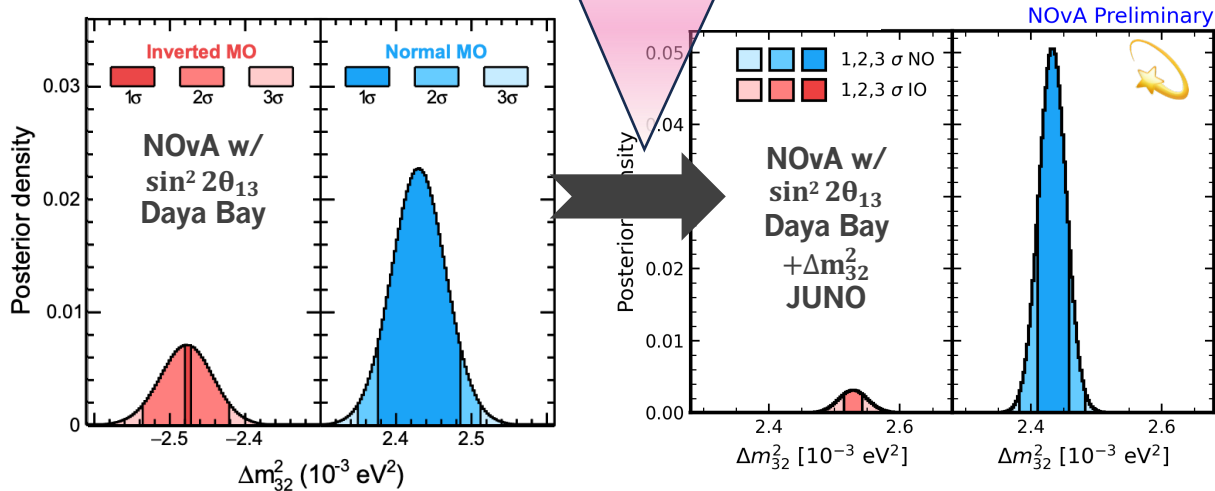
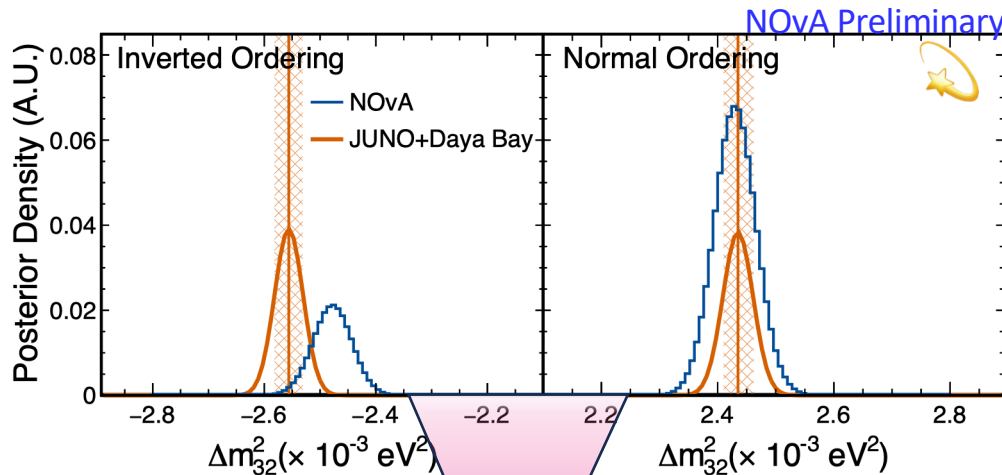
87% / 13%
Posterior density

NOvA + JUNO*

- With JUNO's precision Δm_{32}^2 value, released at Neutrino 2026*, the combined mass ordering preference can be determined.

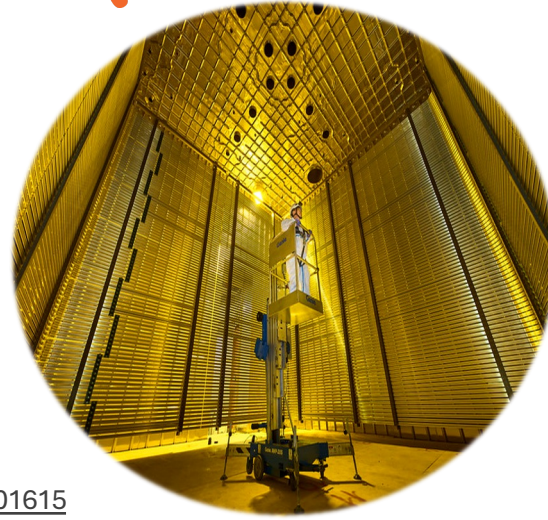
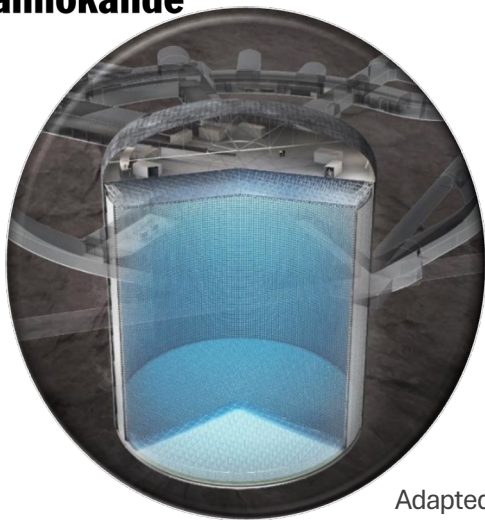
*See JUNO's Talk

External Constraints	Bayes Factor (Normal/Inverted)
NOvA w/ $\sin^2 2\theta_{13}$ Daya Bay	3.3 77% / 23% Posterior density
NOvA w/ $\sin^2 2\theta_{13}$ Daya Bay + Δm_{32}^2 JUNO	15.74* 94% / 6% Posterior density



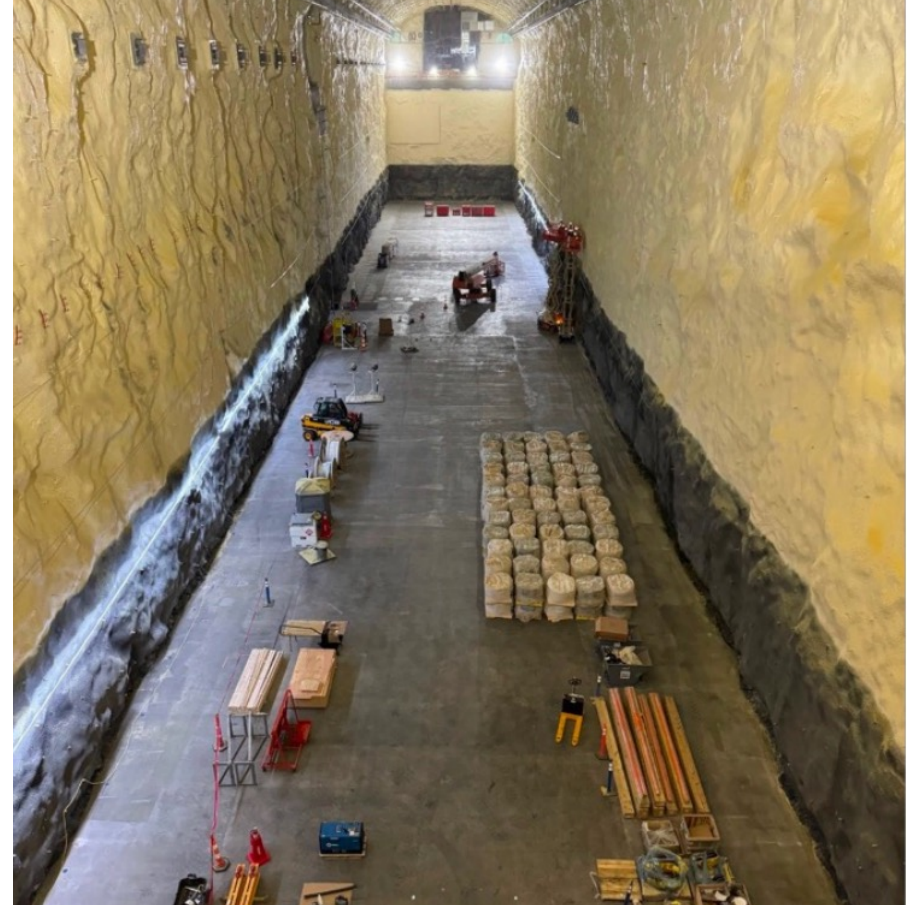
4

The next generation: Hyper-Kamiokande & DUNE



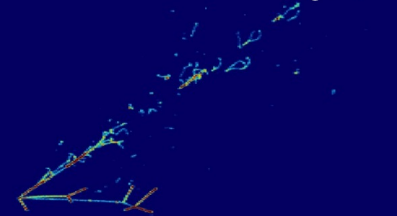
Adapted from [annurev-nucl-102020-101615](https://arxiv.org/abs/annurev-nucl-102020-101615)

	Location	Beam	Baseline	Near Detector	Far Detector
Hyper-K	Japan (Tokai to Kamioka)	J-PARC 1.3 MW	295 km	Suite of detectors, on-and off-axis, intermediate movable Water Cherenkov detector	Water Cherenkov, 187 kt fiducial, off-axis
DUNE	United States (Fermilab to Lead, South Dakota)	LBNF 2 – 2.4 MW tunable	1285 km	Liquid argon time projection chamber + suite of detectors, on-axis, movable off-axis	Liquid argon time projection chamber, 40kt fiducial, on-axis

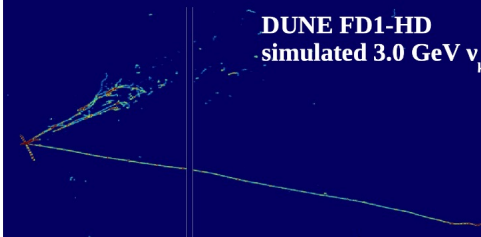


- Excellent particle identification and spatial resolution.
- Low thresholds of a few-MeV.

DUNE FD1-HD
simulated 2.5 GeV ν_e



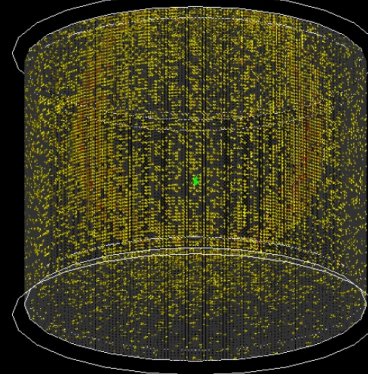
DUNE FD1-HD
simulated 3.0 GeV ν_μ



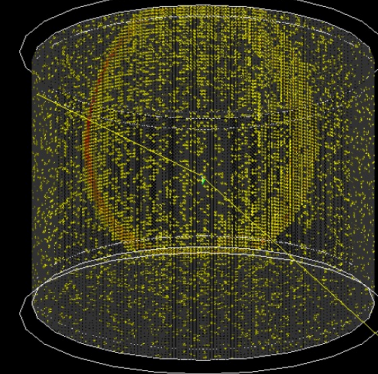
Hyper-Kamiokande

- Clean separation of muon and electron Cherenkov rings.
- Excellent timing resolution ($\sim$ ns).

1 GeV electron



1 GeV muon

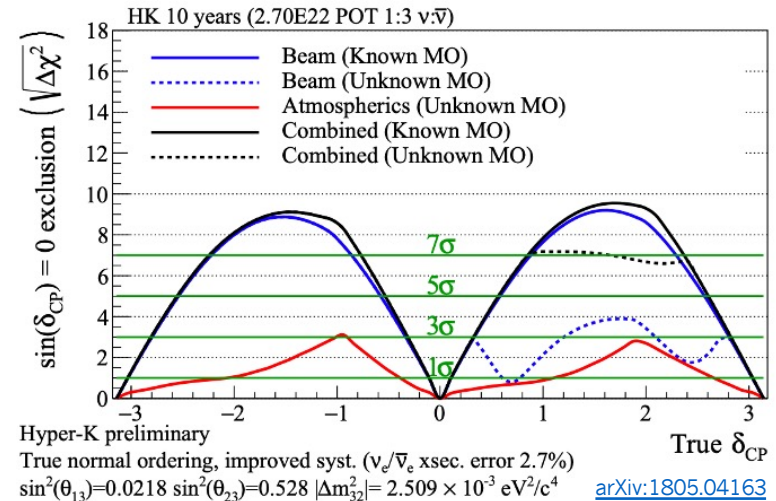


Hyper-K Sensitivity

- Due to its short baseline, HK is unable to break the degeneracy between CPv and MO with only beam data.
- Atmospheric ν 's partially recover CPV sensitivity, or if MO already known through DUNE/JUNO or other experimental input.

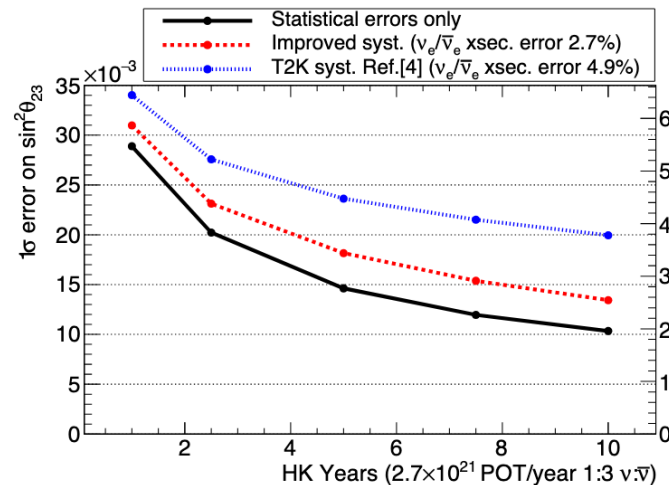
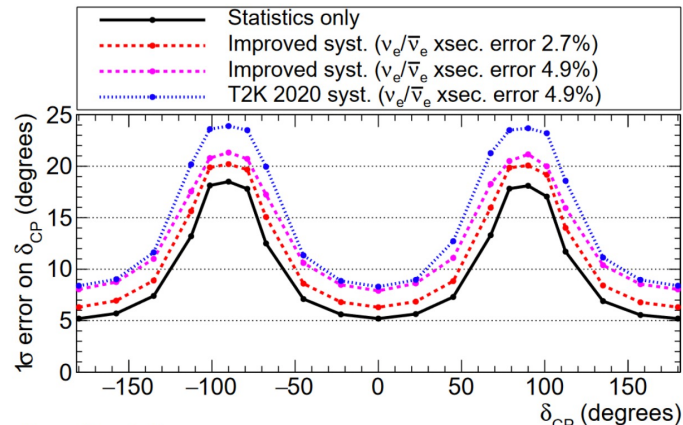
	True $\sin^2\theta_{23}$	Atmospheric ν only	Atmospheric + accelerator ν
Mass ordering	0.40	2.2σ	3.8σ
	0.60	4.9σ	6.2σ
θ_{23} octant	0.45	2.2σ	6.2σ
	0.55	1.6σ	3.6σ

10 years w/ 1.3 MW beam & normal ordering assumed



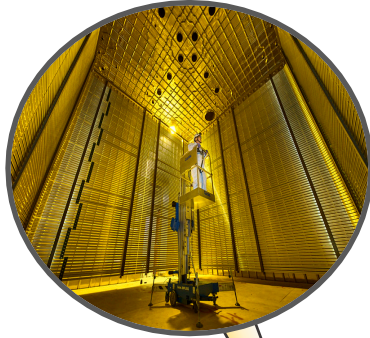
Hyper-K Sensitivity

- Hyper-K has excellent precision on Δm_{32}^2 , δ_{CP} , θ_{23} with multiple years of running.
- It will also probe astrophysical, **solar**, and atmospheric neutrinos, with sensitivity to the solar mixing parameters.

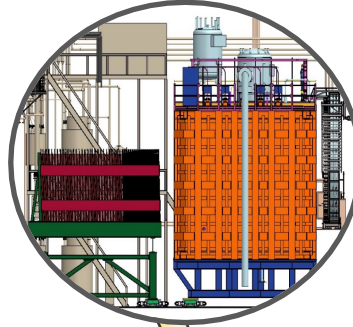


Deep Underground Neutrino Experiment (DUNE)

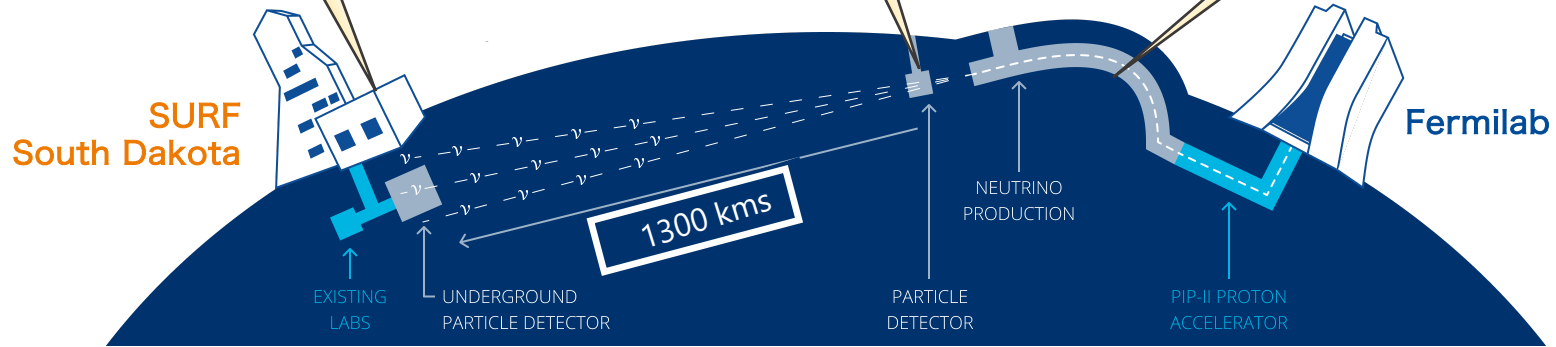
FD: 4 modules of 17 kt
Liquid Argon TPC detector



ND: A suite of detectors to
provide in-situ constraints and
achieve required sensitivities.

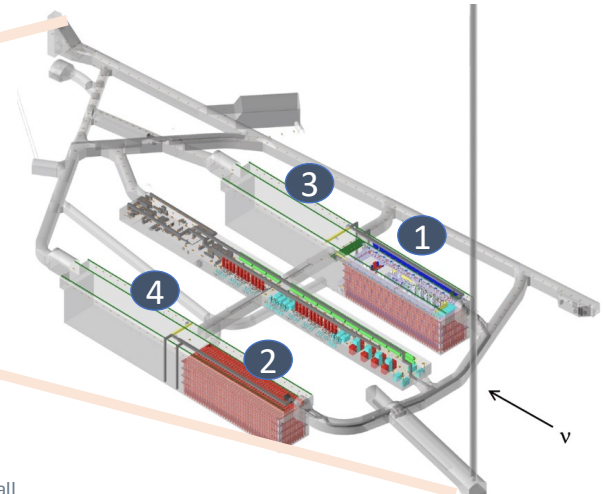
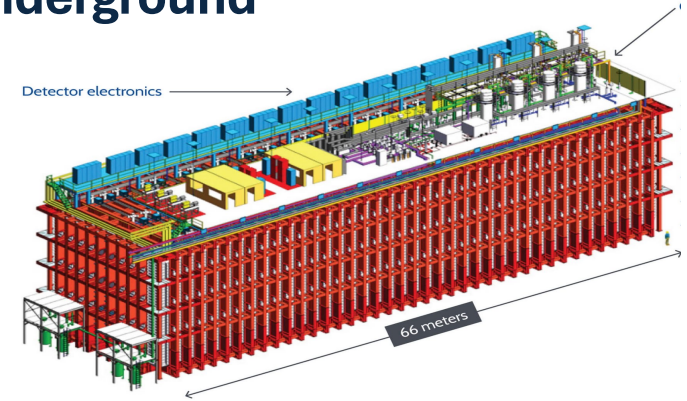
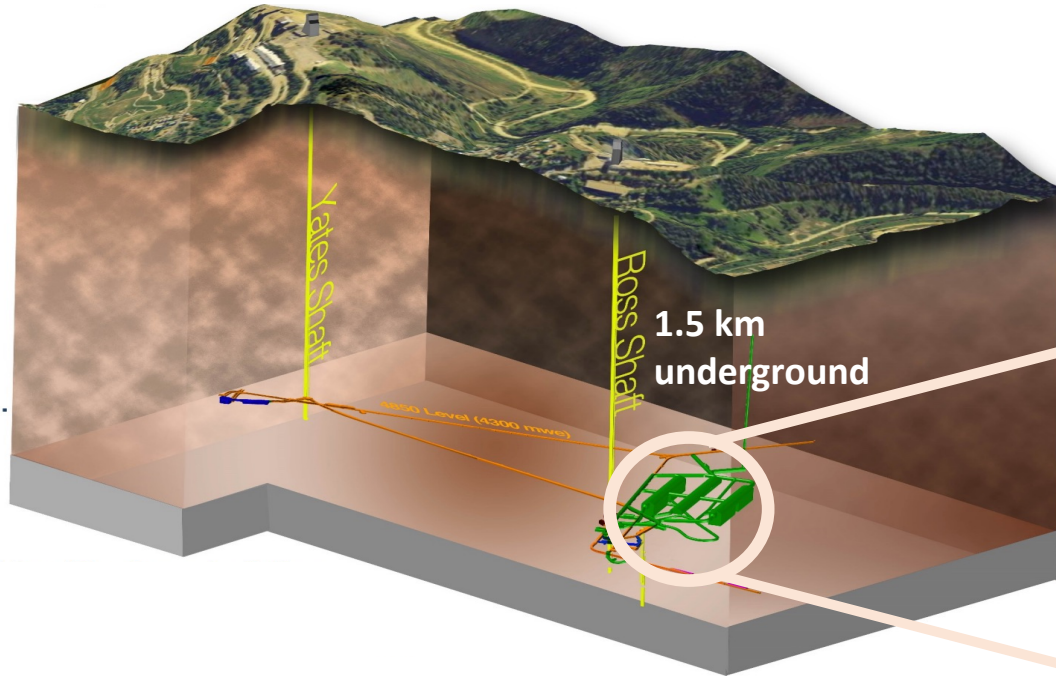


LBNF Beam: Most intense
accelerator neutrino
beam



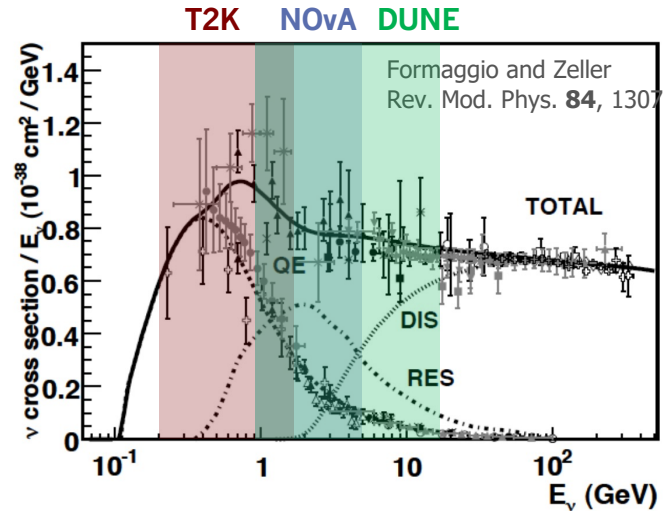
DUNE FD

Located at a baseline of 1300 km from the beam target and 1.5 km underground



DUNE FD: LArTPC Technology

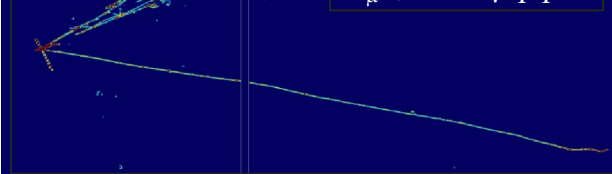
- Exquisite imaging for flavor ID and energy reconstruction.
- Excellent particle identification and spatial resolution.
- Low thresholds for charged particles enables precise reconstruction of lepton and hadronic energy.

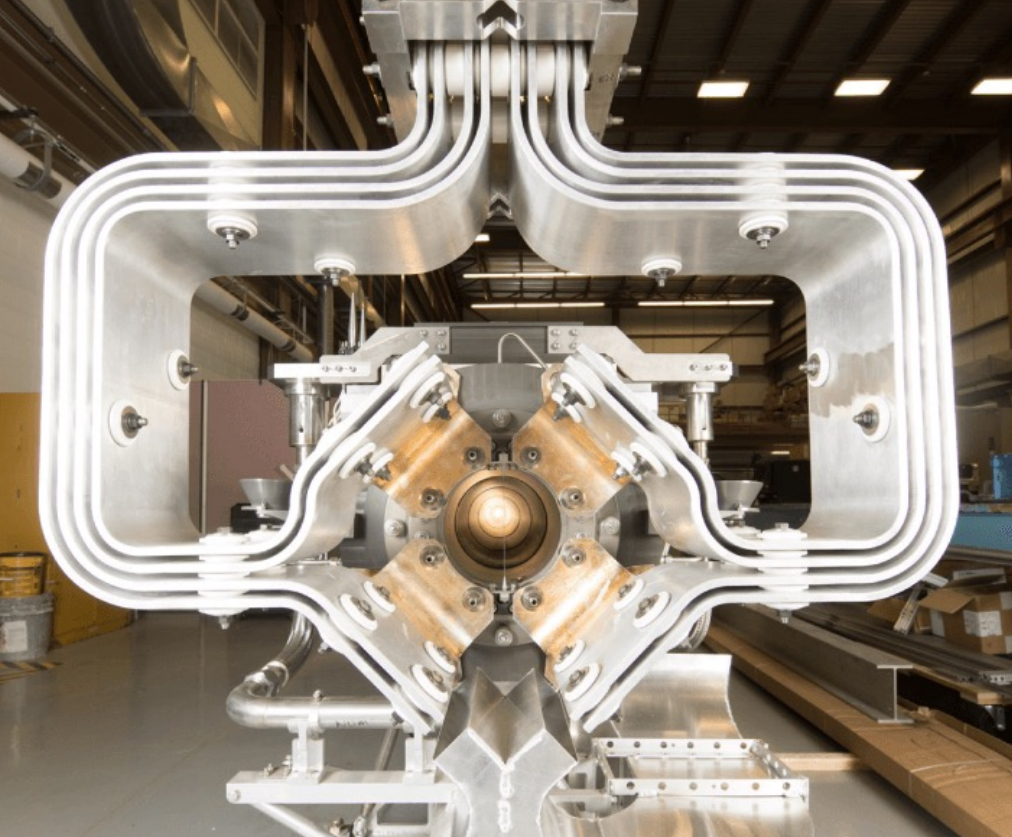


DUNE FD1-HD
simulated 2.5 GeV ν_e
 $\nu_e + \text{Ar} \rightarrow e p p \pi$

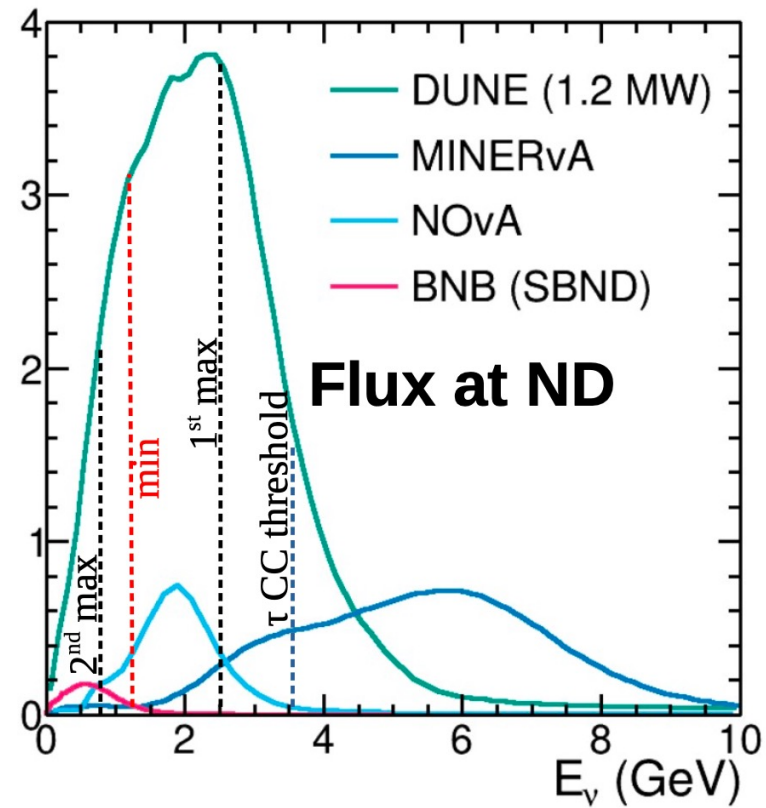


DUNE FD1-HD
simulated 3.0 GeV ν_μ
 $\nu_\mu + \text{Ar} \rightarrow \mu p p \pi^0$





$\nu_\mu/\text{cm}^2/\text{GeV}/\text{year} (\times 10^{12})$

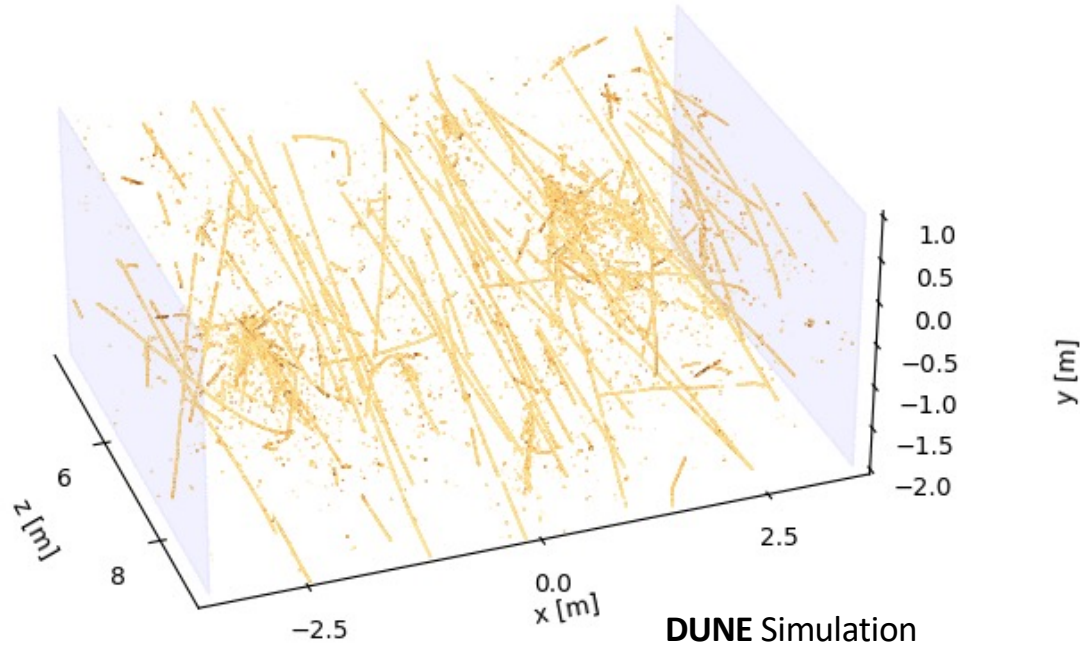


LBNF PIP-II BEAM: **MOST POWERFUL** ACCELERATOR
NEUTRINO BEAM IN THE WORLD

DUNE sits on-axis and will sample the broad beam!

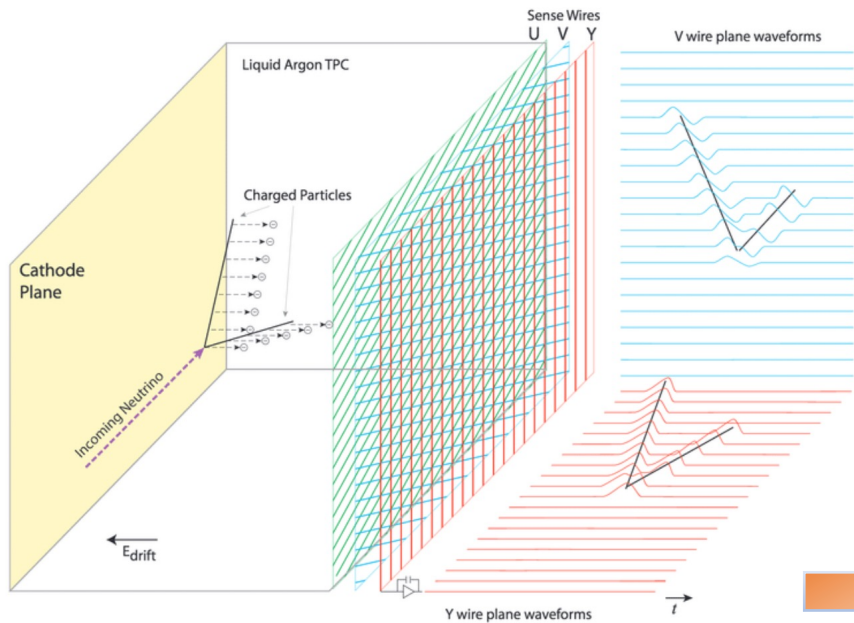
With great power ...

COMES GREAT PILE-UP

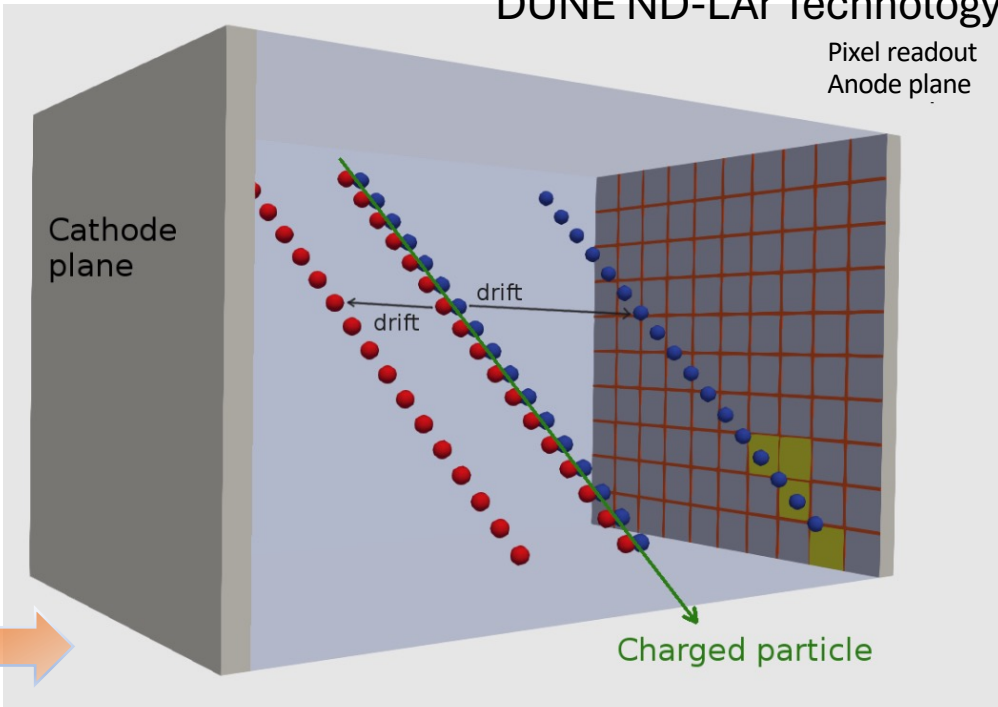


~100 ν interactions at DUNE ND in a single LBNF beam spill

DUNE FD Technology



DUNE ND-LAr Technology



DUNE ND-LAr: Powered by Pixels

DUNE ND-LAr

1. Modular TPC

- ☐ short drift distances

2. Pixelated Charge readout

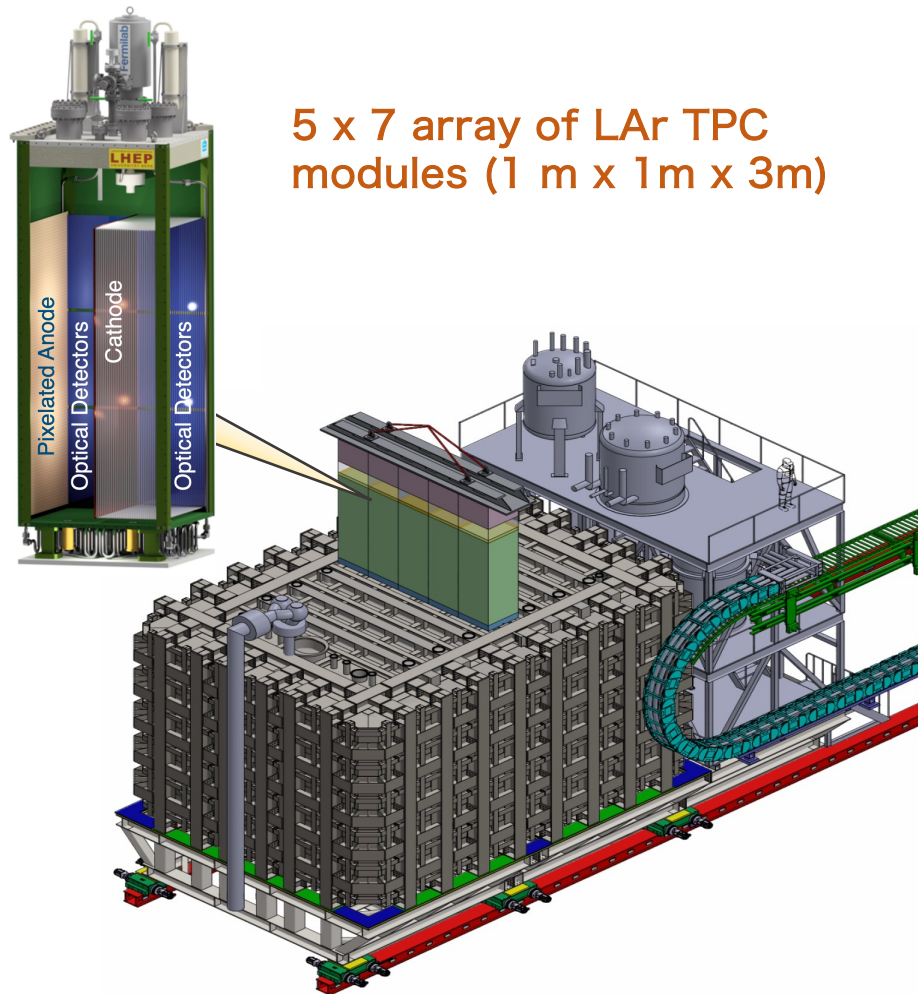
- ☐ unambiguous 3D tracking

3. Optical Segmentation

- ☐ contained scintillation light

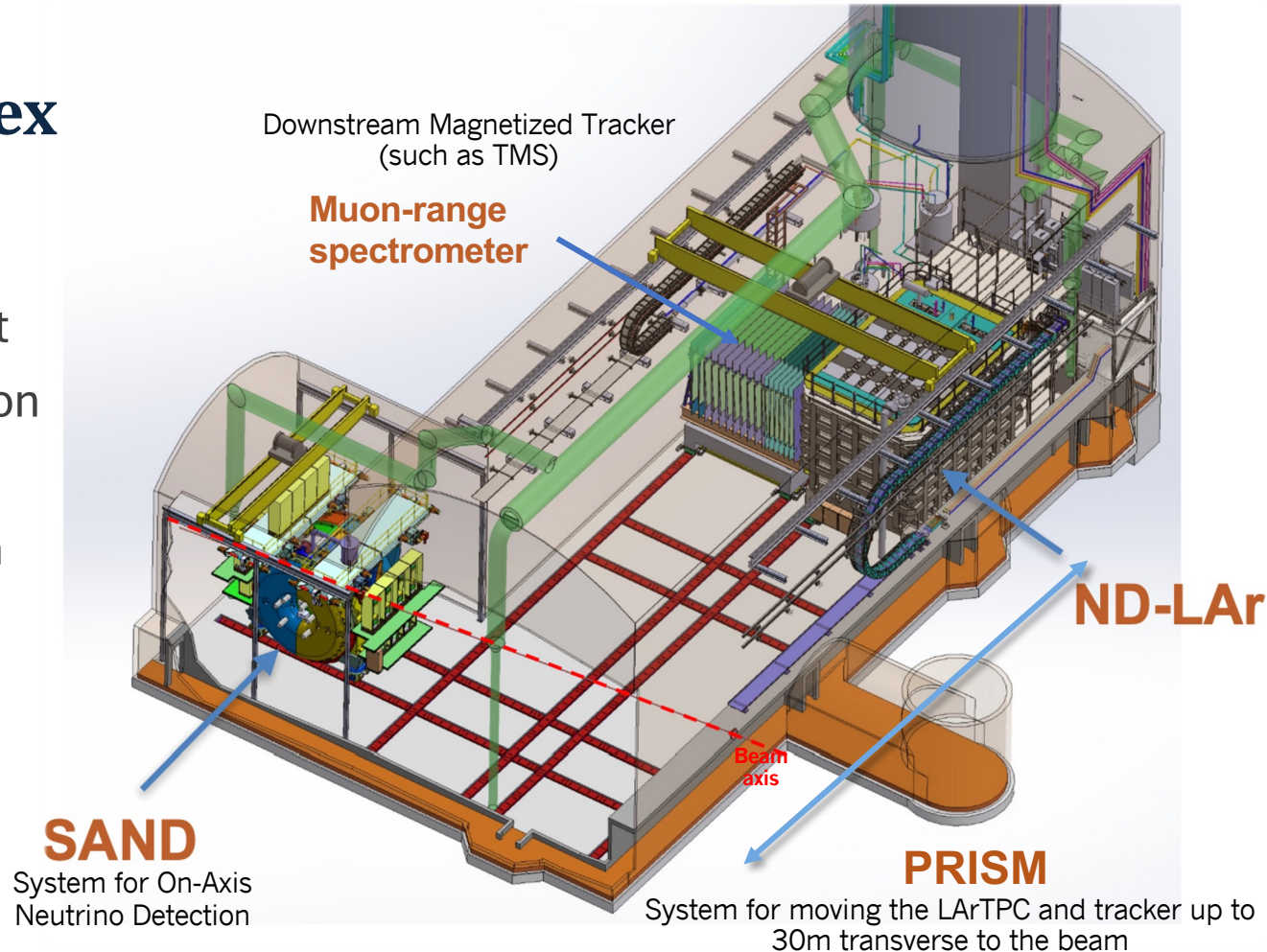
4. Low-profile field cage

- ☐ limit inactive volume

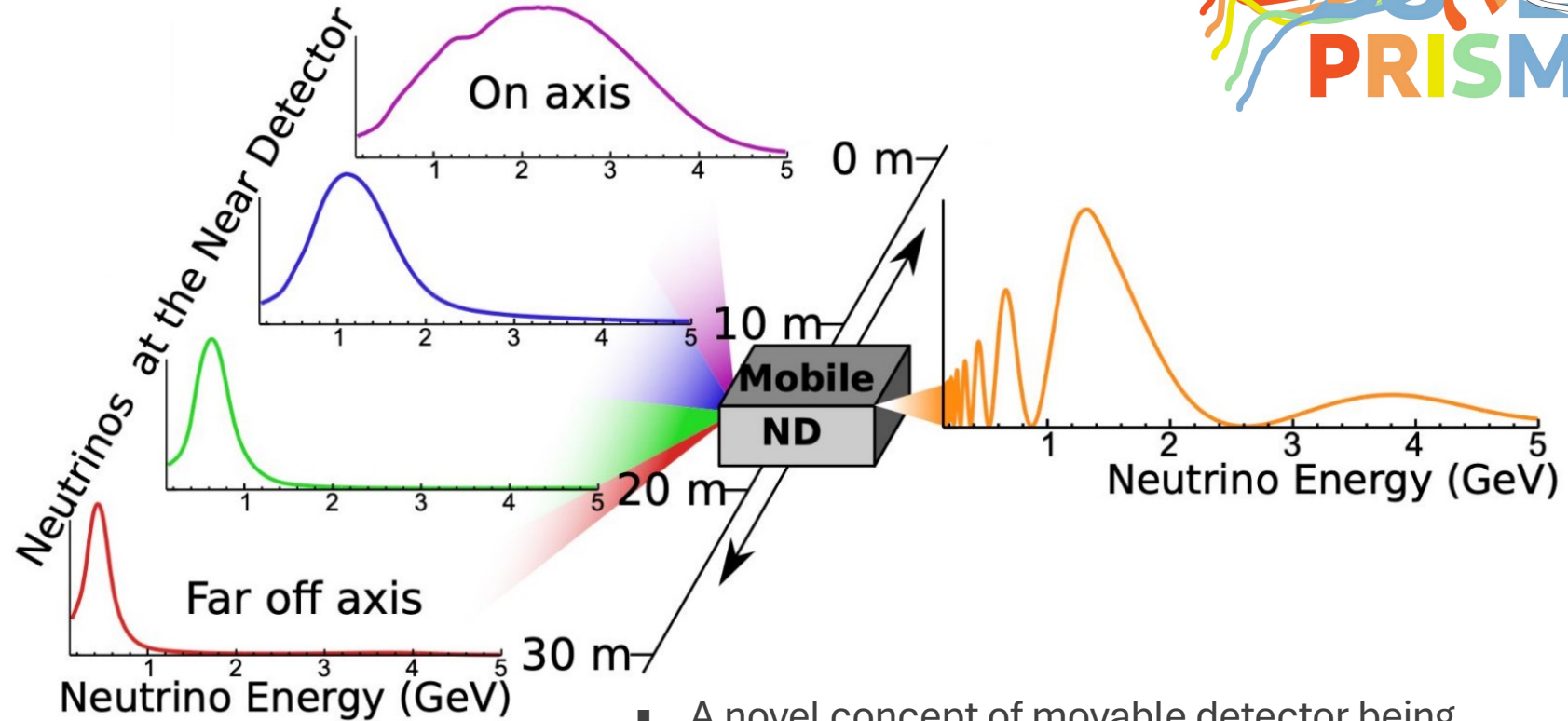


DUNE ND Complex

- Combined best-practices from current and previous generation of long-baseline experiments to design the ND.
- DUNE's physics goals and precision needs require it!

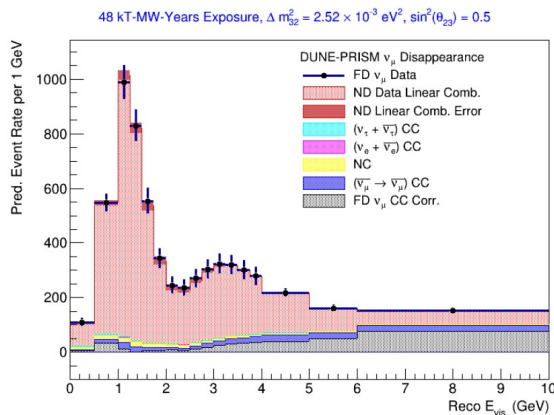
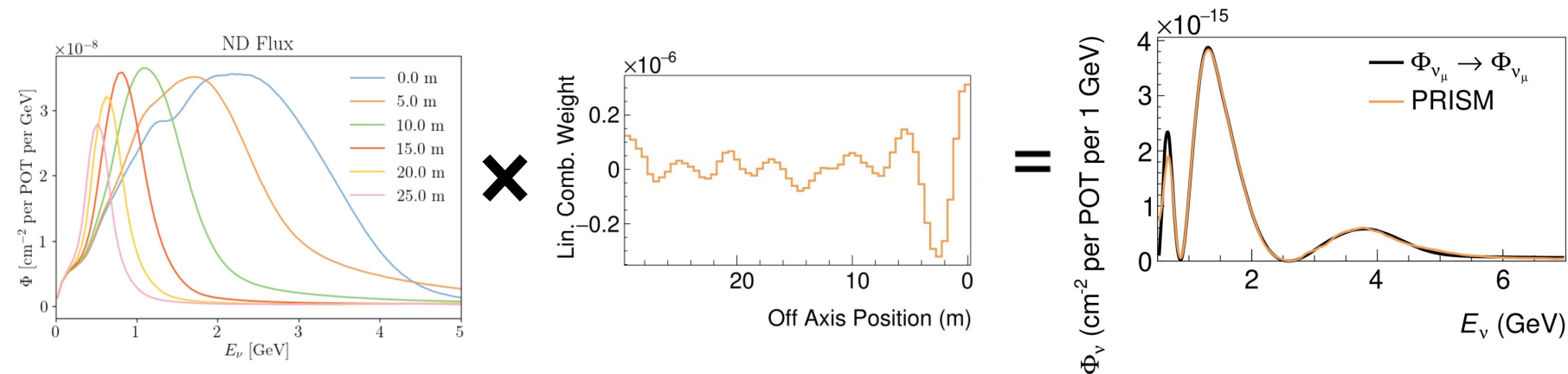


DUNE PRISM



- A novel concept of movable detector being implemented by DUNE (and Hyper-K) for the first time!

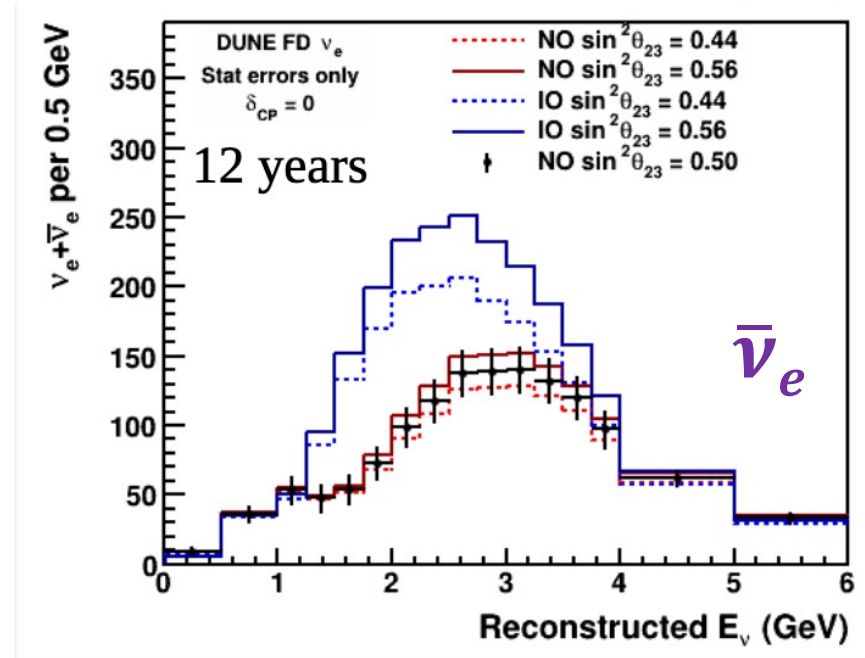
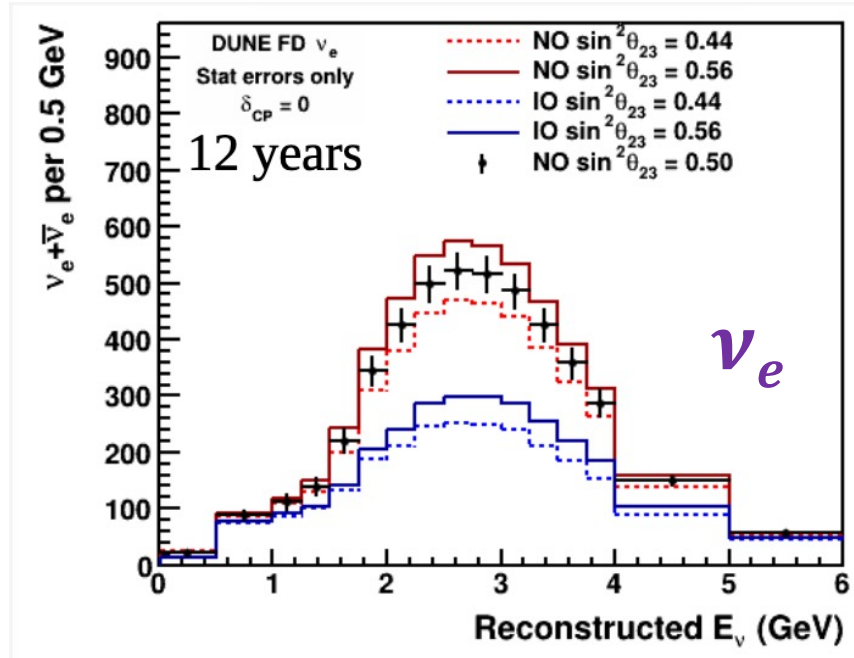
DUNE PRISM



- Using a linear combination of ND flux at various off-axis position, we can construct a prediction that matches the oscillated FD flux
- Reduces dependencies on simulated models to do Near to Far matching.

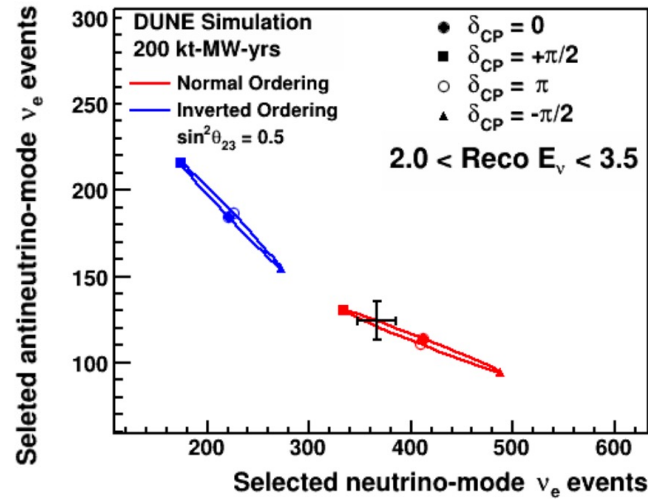
DUNE Future Data

- DUNE data has spectra information.
- With 10,000s of ν_μ and 1000s of ν_e collected over 10 years, DUNE will conclusively determine the mass ordering and have excellent potential to discover CP violation.



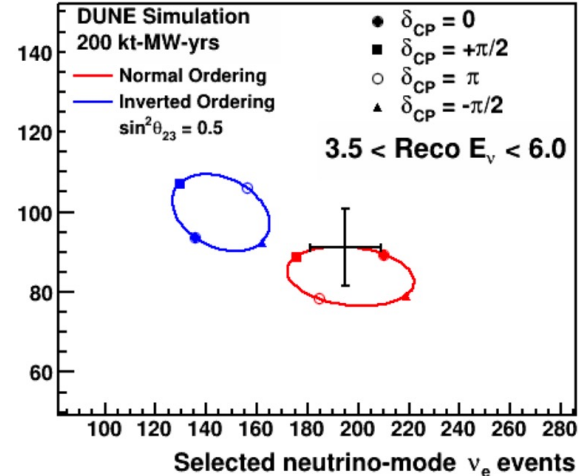
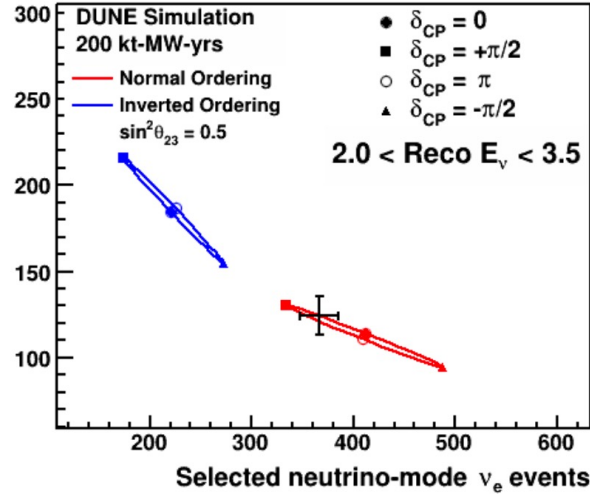
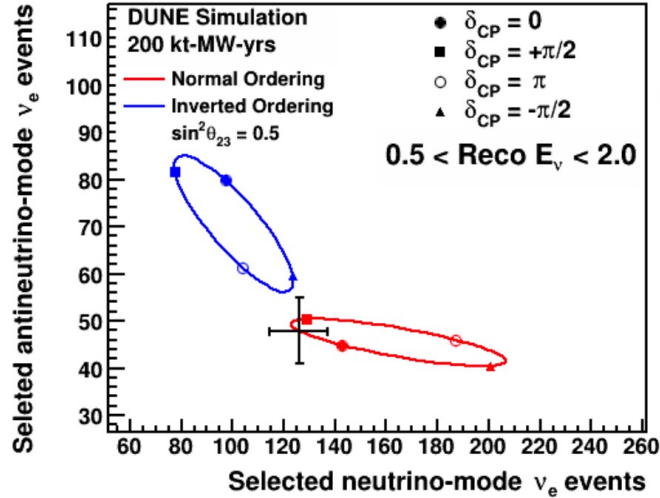
DUNE Sensitivity

- DUNE's longer baseline and correspondingly higher neutrino energy, completely removes the degeneracy between the measurements of mass ordering and δ_{CP}



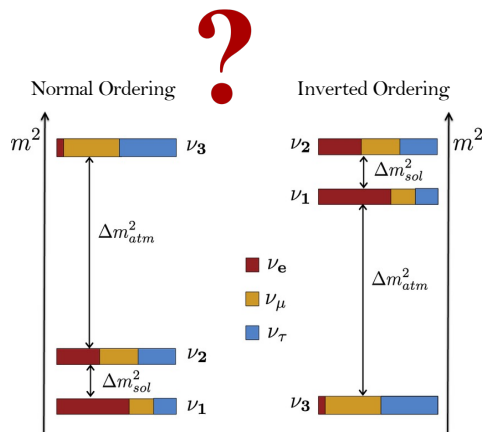
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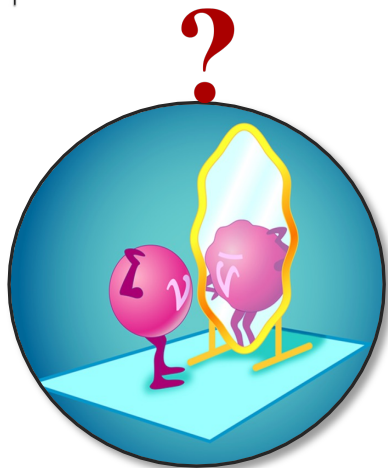
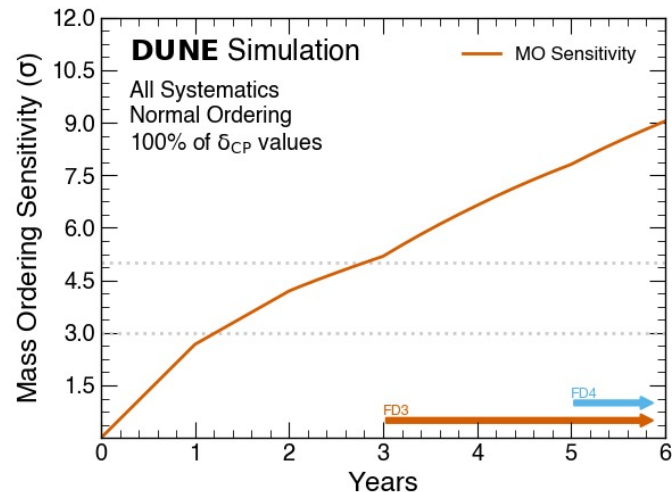


- DUNE can measure oscillation parameters in many different bins of L/E.
- If 3-Flavor paradigm is robust, data should give the same answer every time.

DUNE Goals: Discovery

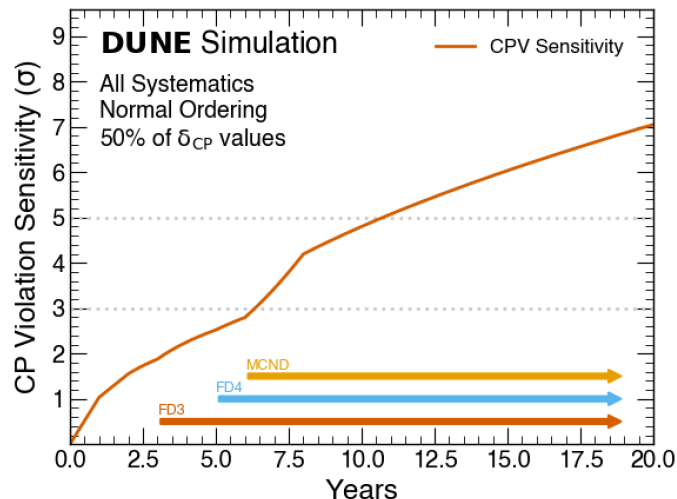


Early milestone: DUNE will resolve MO within 1-5 years of running.

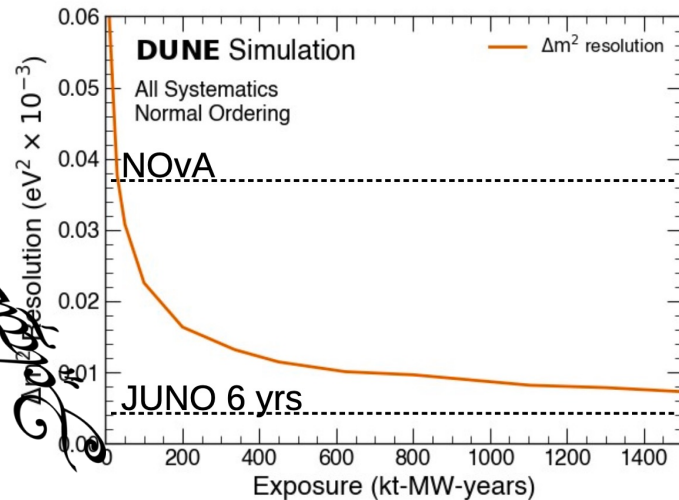
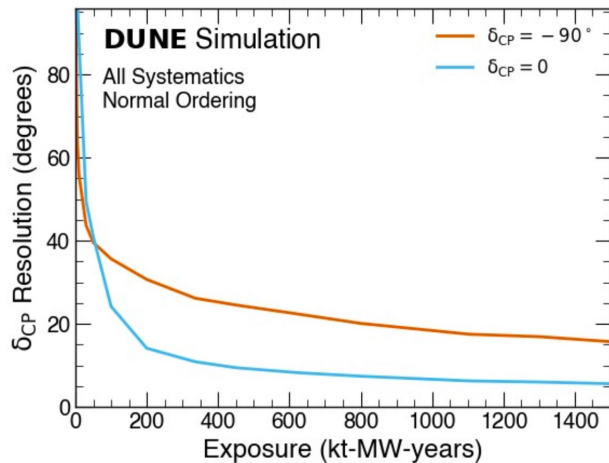


δ_{CP} : Do neutrinos violate CP?

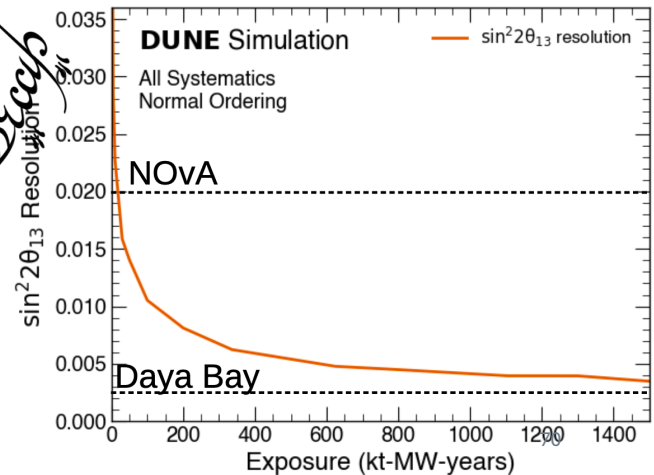
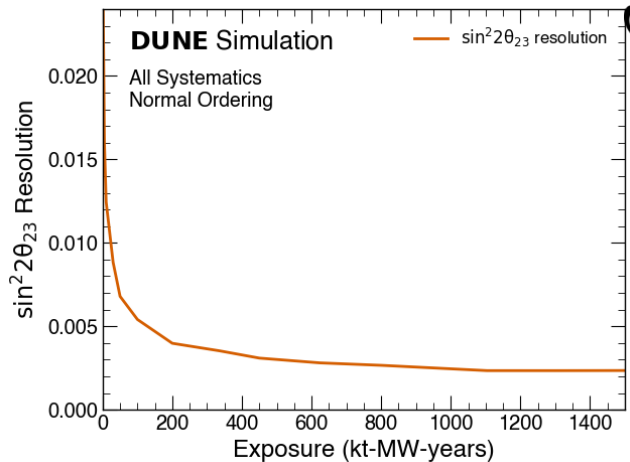
DUNE has $> 5\sigma$ discovery potential for $> 50\%$ of δ_{CP} values for either MO.



DUNE Goals: Precision



DUNE is the best-in-class experiment that will make unambiguous high precision measurements of Δm_{32}^2 , δ_{CP} , θ_{23} and θ_{13} with a single experiment.



5

What's next?

More neutrinos are coming

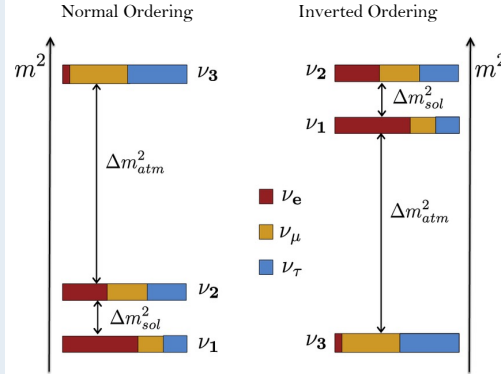


A new generation of experiments are underway or about to launch in the next 5 years!

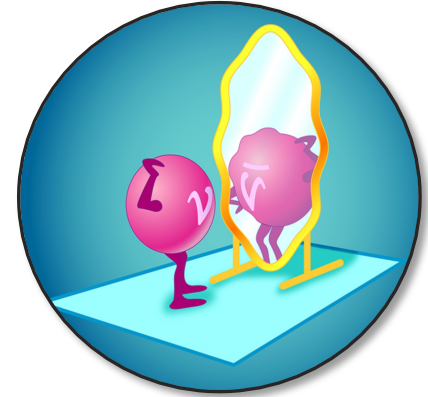
We are entering the era of discovery and precision!



Mass Ordering(MO): Normal or Inverted?



δ_{CP} : Do neutrinos violate CP?

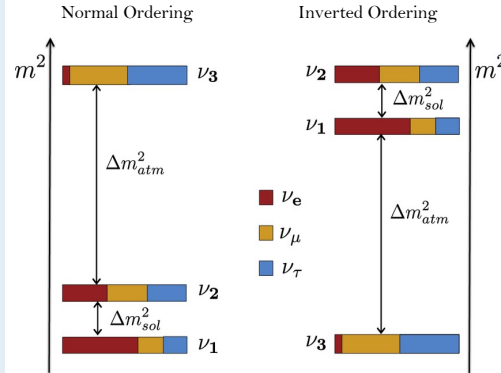


We are entering the
era of discovery and
precision!

BUT,
keep room
for surprises!

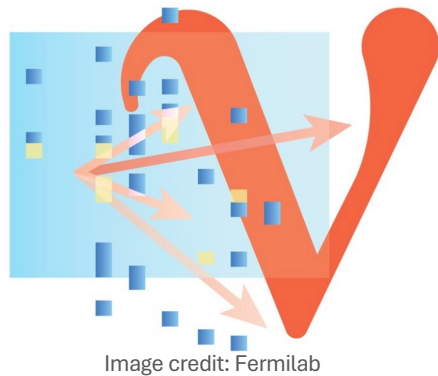


**Mass Ordering(MO): Normal or
Inverted?**



**δ_{CP} : Do neutrinos
violate CP?**





THANK
YOU!

Key takeaways

- Three generations of long-baseline experiment: K2K/MINOS/OPERA → T2K/NOvA → HK/DUNE.
- T2K and NOvA continue to deliver world-leading measurements, but CP-violation and the mass ordering remain unresolved. Joint fit delivers complementary information.
- Reactors anchor θ_{13} and add an independent handle on the ordering.
- Hyper-K (statistics, CP) and DUNE (matter effect, ordering) are complementary by design.
- The next decade would deliver definitive answers on CP violation and the mass ordering!