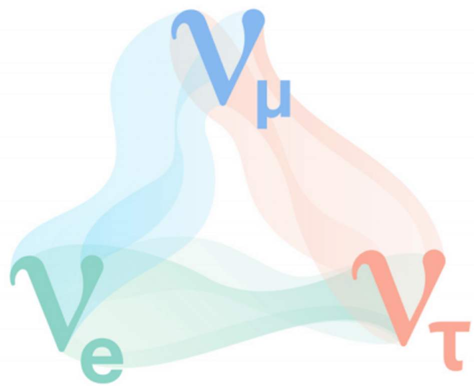
Caltech

Exploring the neutrino sector with long-baseline experiments

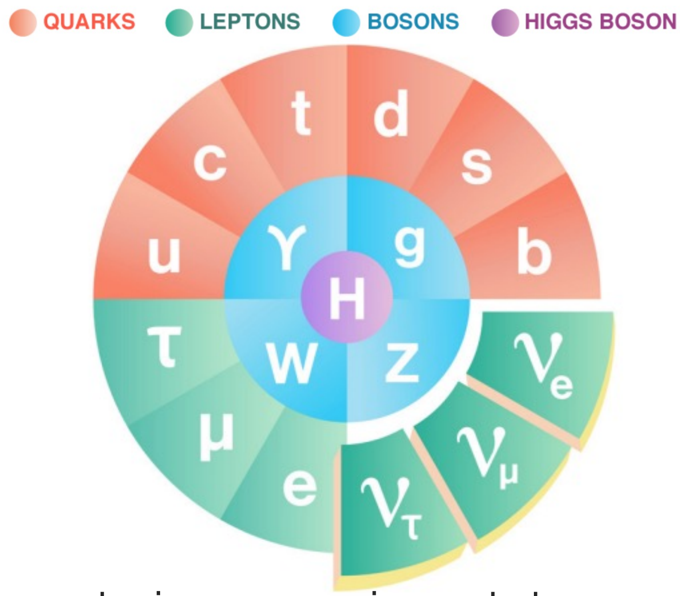


Zoya Vallari

Rising Star Symposium
23 September 2021

[zoya@caltech.edu]

The Neutrino Sector



$$|\nu_\alpha\rangle = U^*_{\alpha j}\,|\nu_j\rangle$$

$|\nu_\alpha\rangle$ Flavor eigenstate

$|\nu_j\rangle$ Mass eigenstate

- Neutrinos interact in flavor eigenstates but propagate in mass eigenstates.
- The in-flight oscillation between flavor can be parameterized by mixing angles between the mass states.

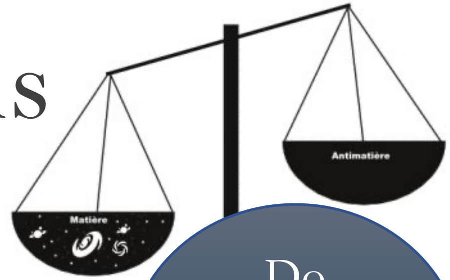
$$P\left(\nu_\alpha \to \nu_\beta\right) = \left|\sum_j U^*_{\alpha j} e^{-i m_j^2 L/2E} U_{\beta j}\right|^2$$

PMNS Mixing Matrix

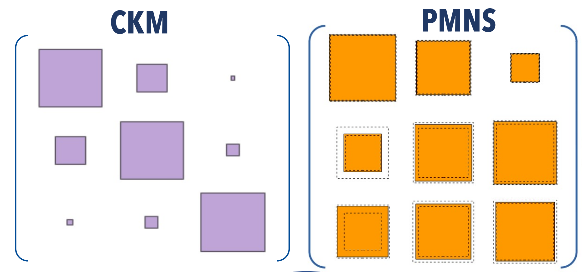
$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Open Questions

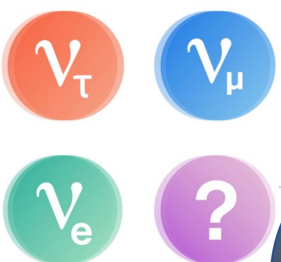


Do neutrinos violate CP?

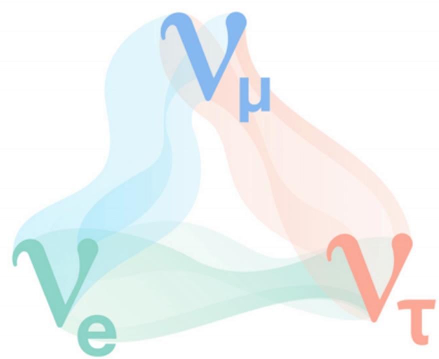


Contrast b/w CKM & PMNS matrix?

Are neutrinos Majorana or Dirac?



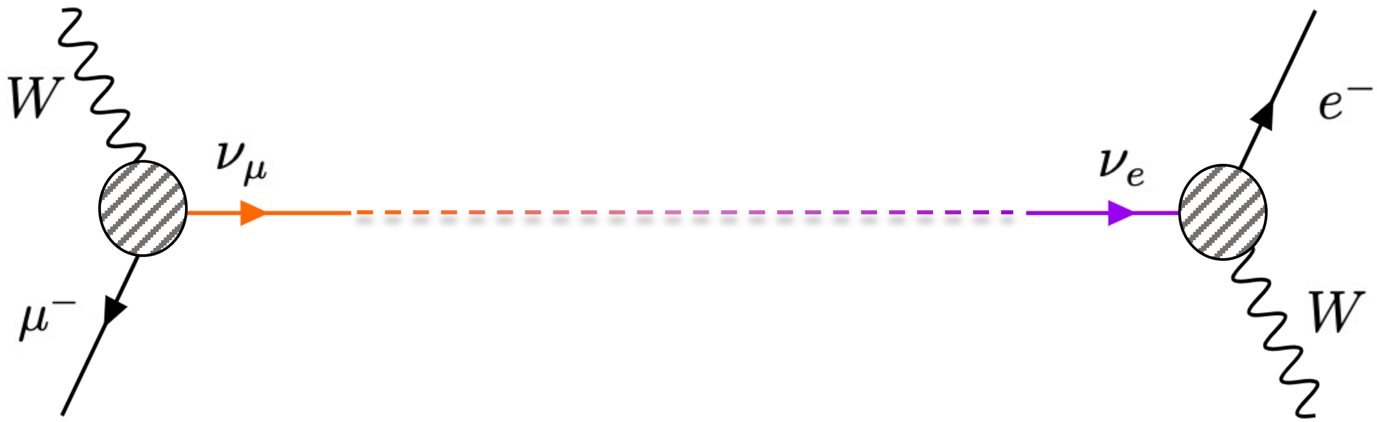
Existence of sterile neutrinos?



How do neutrinos get mass?

Neutrino masses and their ordering?

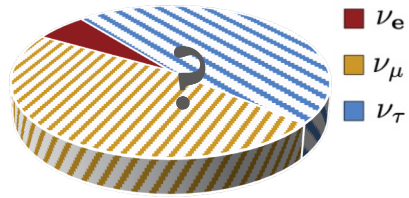
Long-Baseline (LBL) Searches



Long-baseline (LBL) neutrino oscillation experiments measure $\nu_e(\overline{\nu}_e)$ oscillations in ν_μ ($\overline{\nu}_\mu$) beam created by proton accelerators.

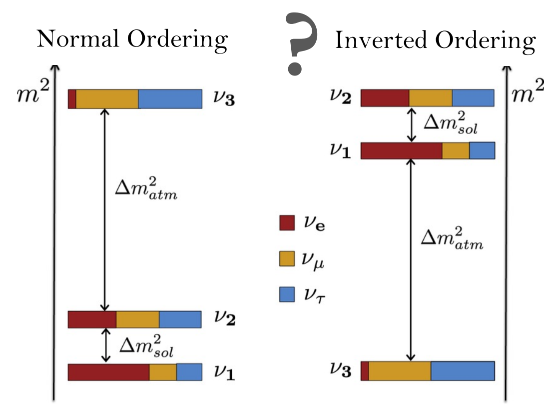
In focus: LBL 3-flavor oscillation physics

1. θ_{23} : Is the mixing maximal?



Large uncertainty on θ_{23} mixing angle
Is the amount of $\nu_\mu = \nu_\tau$? $\theta_{23} = 45^o$?

2. Mass Ordering: Normal or Inverted?

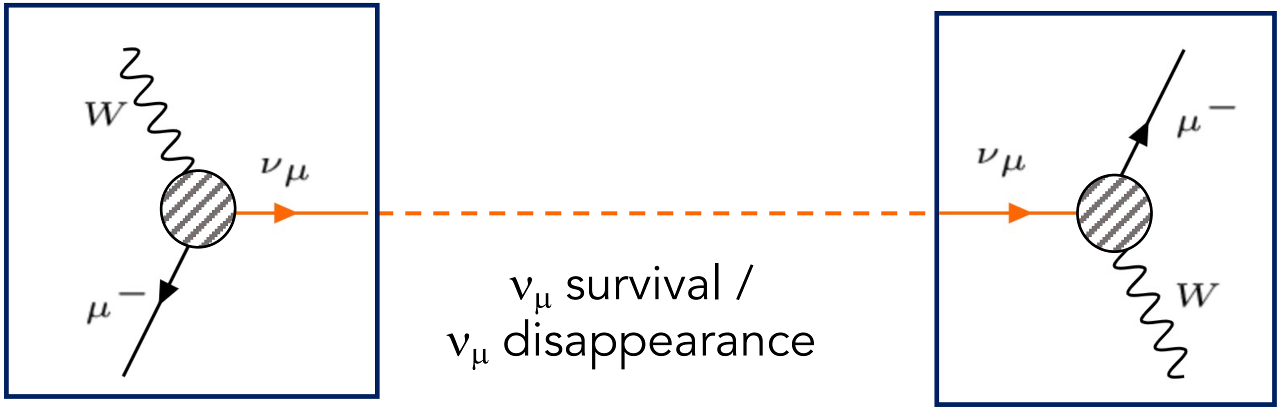


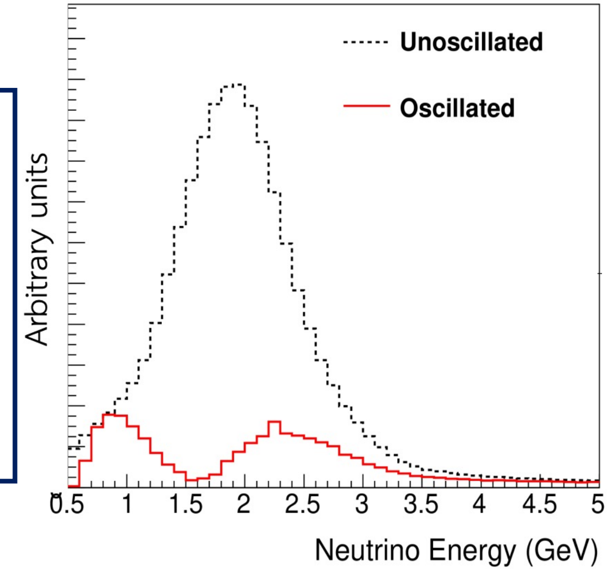
Does the symmetry that determines the mass of charged leptons influences ν_1 to be the lightest neutrino or does the inverse hold?

3. δ_{CP}: Do neutrinos violate CP?

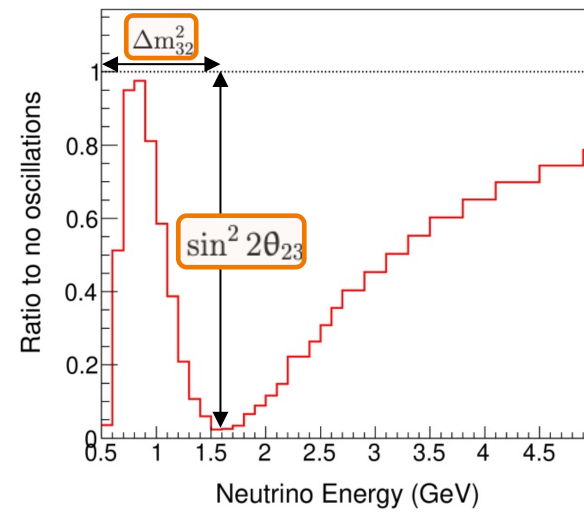
Do neutrinos and antineutrinos oscillate at the same rate? CP violation in leptonic sector could provide a path towards explaining the baryon asymmetry in the early universe.

LBL Oscillations : ν_μ disappearance



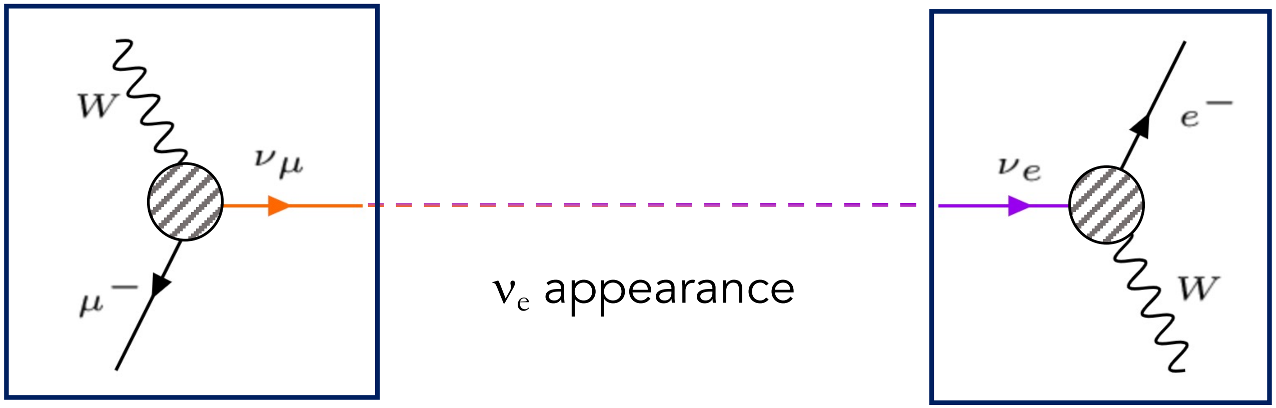


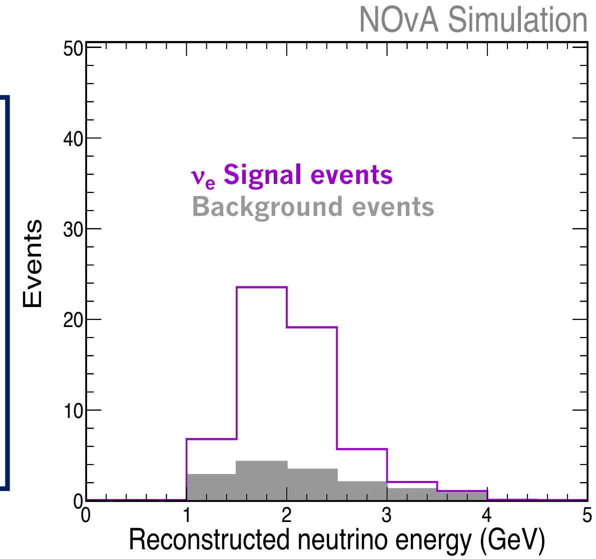
$$P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu\right) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$



- Leading order dependence on Δm^2_{32} and $\sin^2\theta_{23}$
- Aims to answer the question of **maximal mixing in θ_{23}**

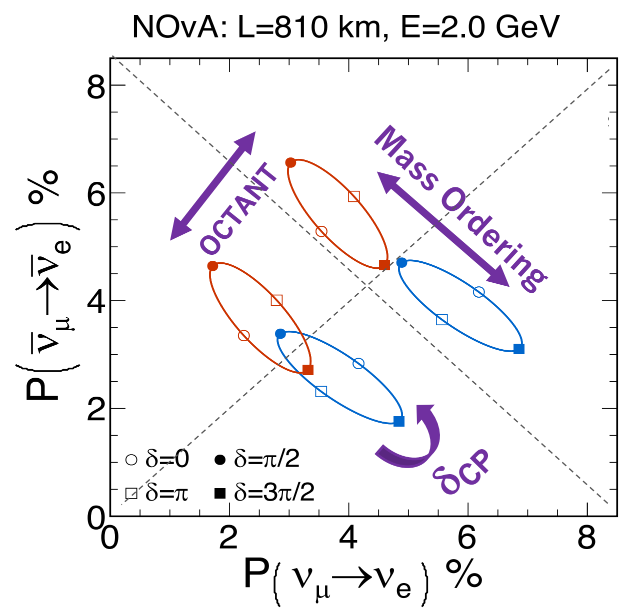
LBL Oscillations : ν_e appearance



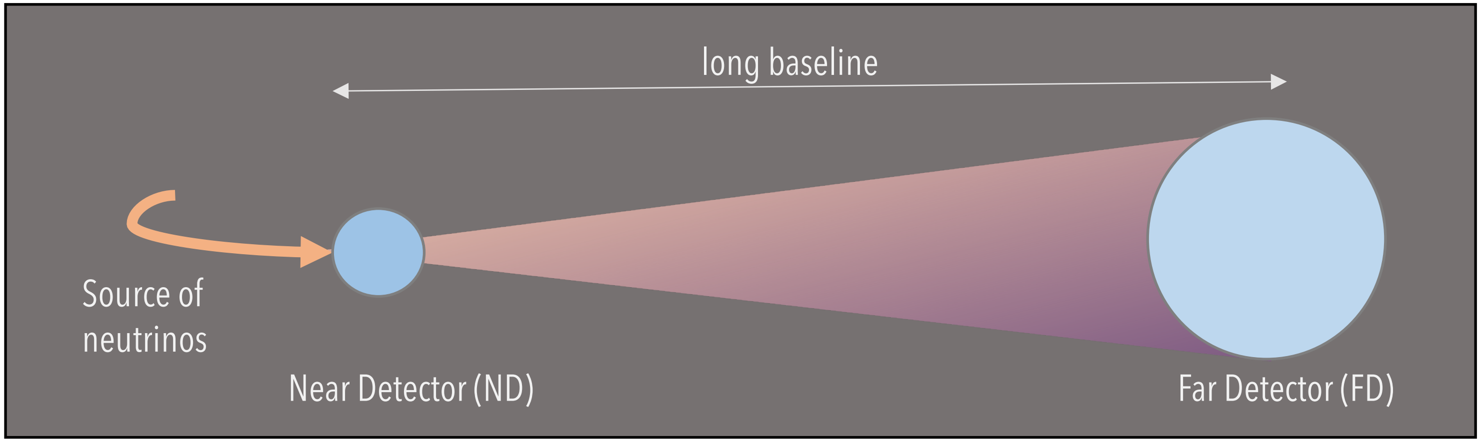


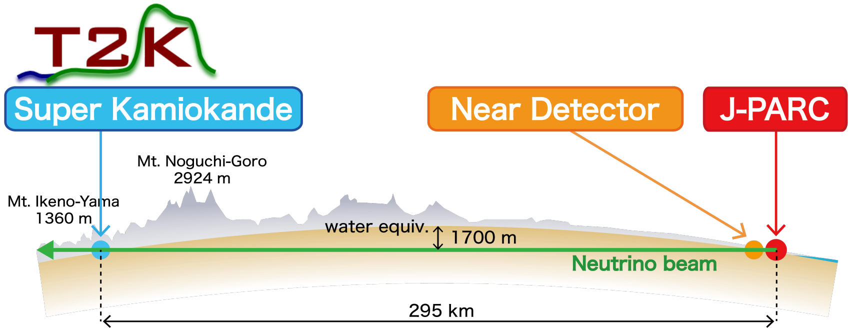
- Comparing the rate of ν_e appearance with $\overline{\nu}_e$ appearance provides a measurement of δ_{CP} and mass ordering.

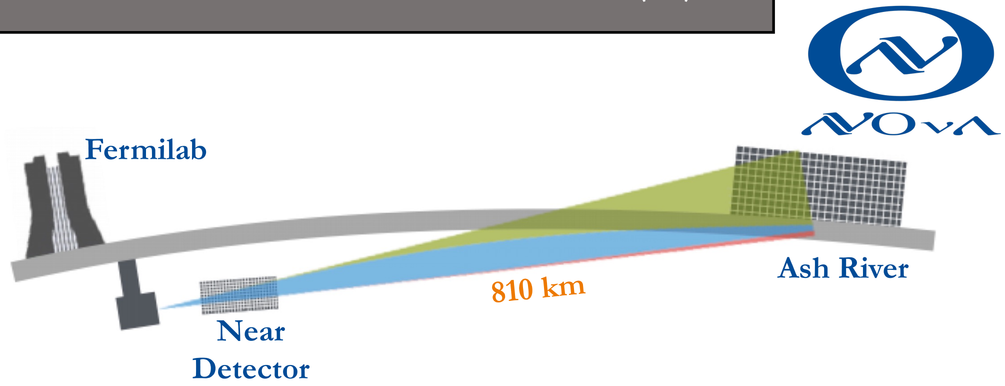
- **δ_{CP} and mass ordering have inverse dependence on probability of ν_e and $\overline{\nu}_e$ appearance** while changing the octant is symmetric for the two beam modes.

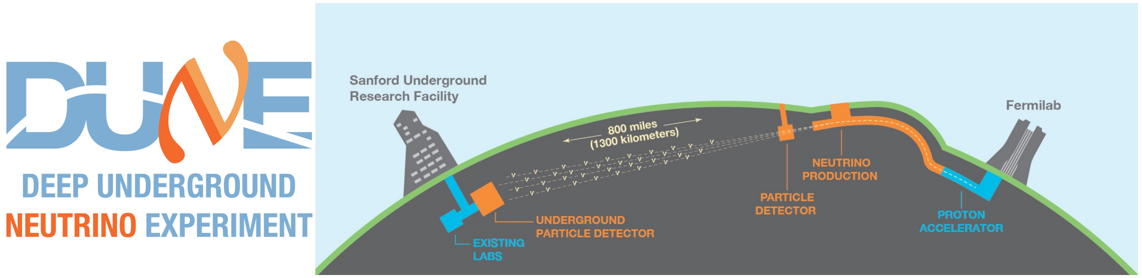


Long-Baseline Experiments

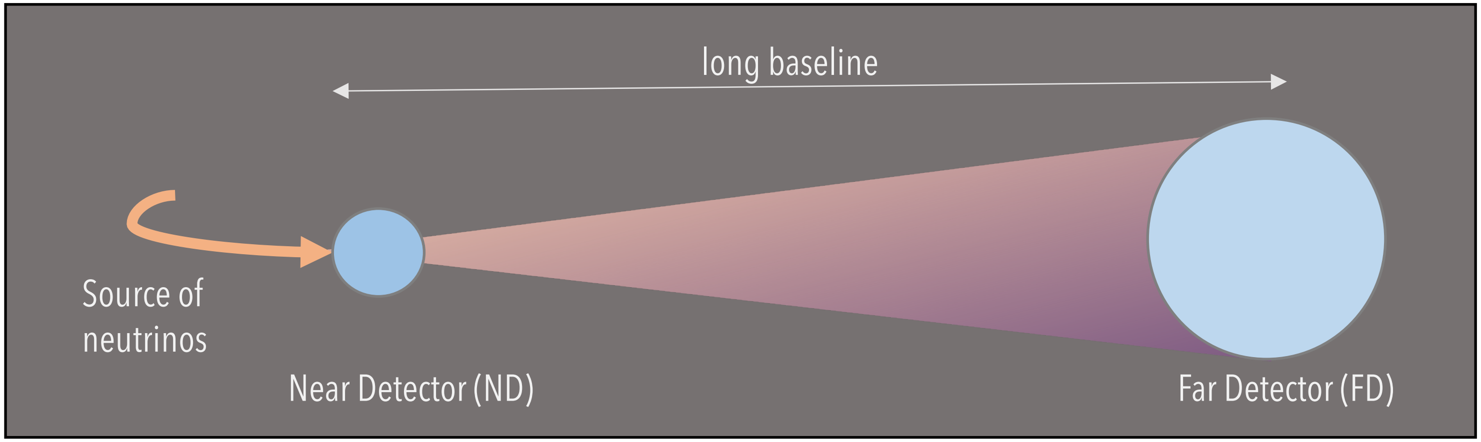


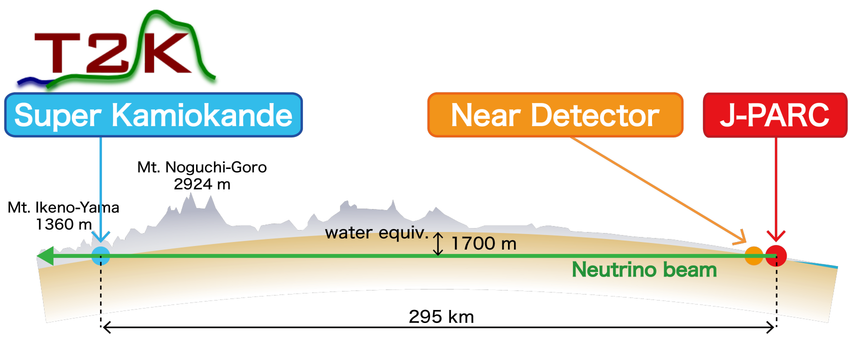


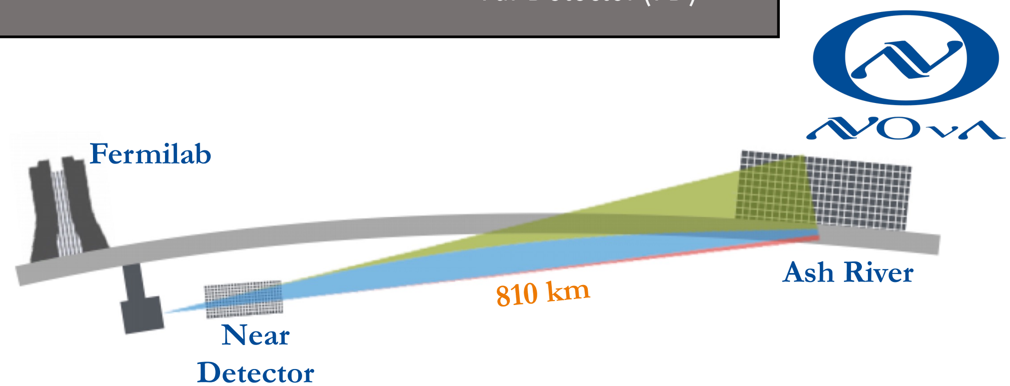




Long-Baseline Experiments

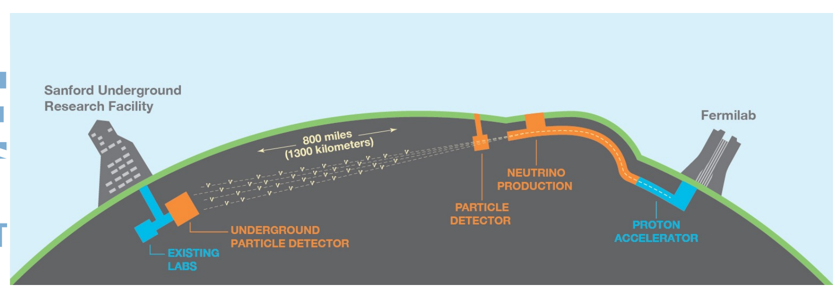






Coming Soon

DEEP UNDERGROUND NEUTRINO EXPERIMENT



Also, coming soon: **Hyper-Kamiokande**

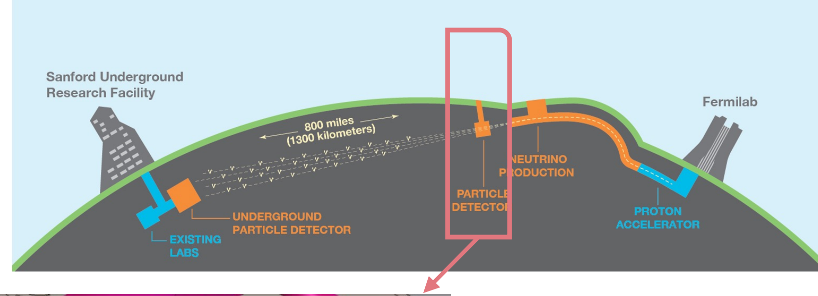
Near Detector – Our favorite ally!

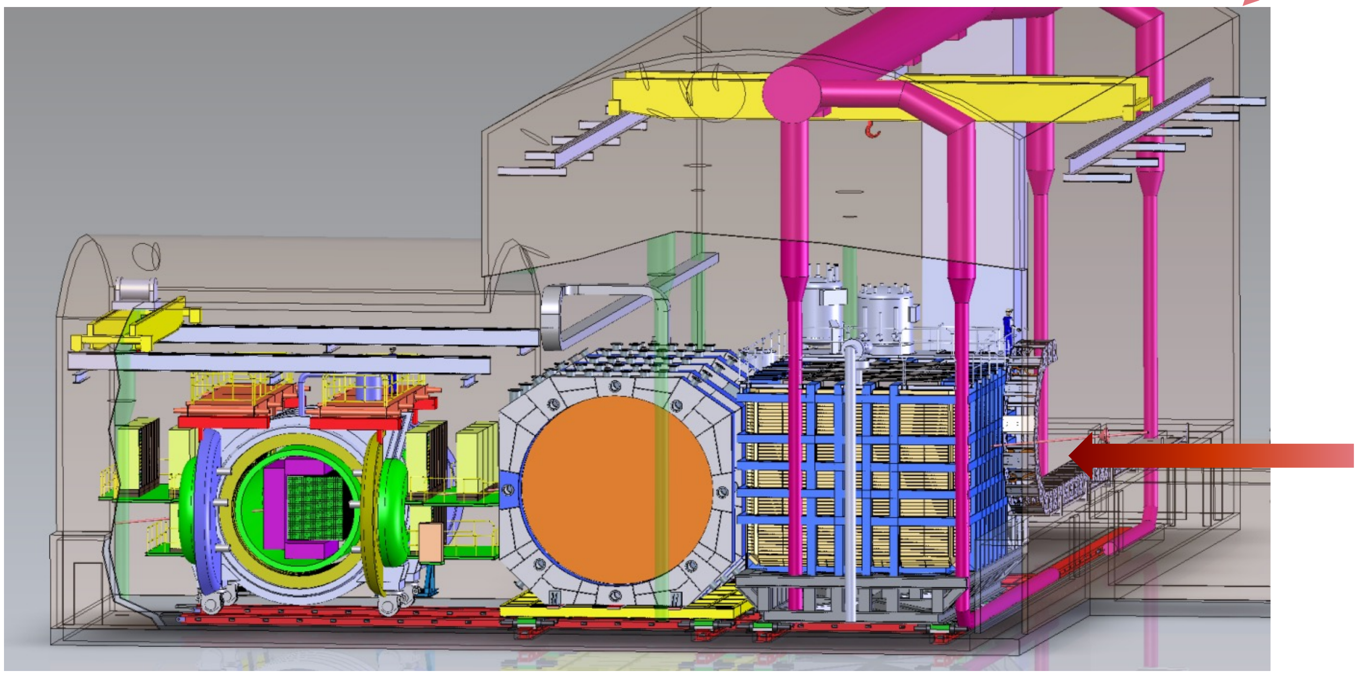
- Near Detector provides valuable constraints on:
  - neutrino flux
  - cross-section, and
  - detector uncertainties

$$\underset{\text{Events at FD}}{R(\vec{\mathbf{x}})} = \underbrace{\overbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(\nu_A \to \nu_B)}_{\text{Far}}$$

- While external measurements have brought down the uncertainties in the model, an in-situ measurement at ND is the most effective way to constrain these large sources of uncertainty.

DUNE Near Detector

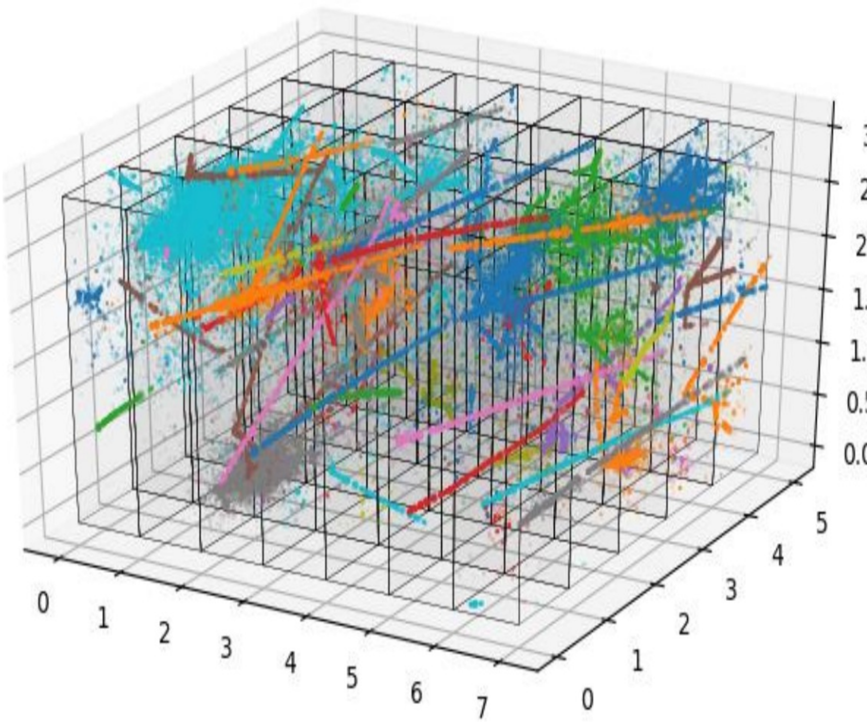




- DUNE will feature the most powerful neutrino beam.
- With ND located at ~600m from the beam target, the event rate of neutrino interaction would be extremely high.

Modular TPCs - ArgonCube

- Optically isolated modular TPCs array to collect charge and light signals.
- Each TPC module will have a pixelized charge readout that allows for a simple 3D reconstruction of tracks.
- A prototype detector is currently being built . Successful run of Module-0.



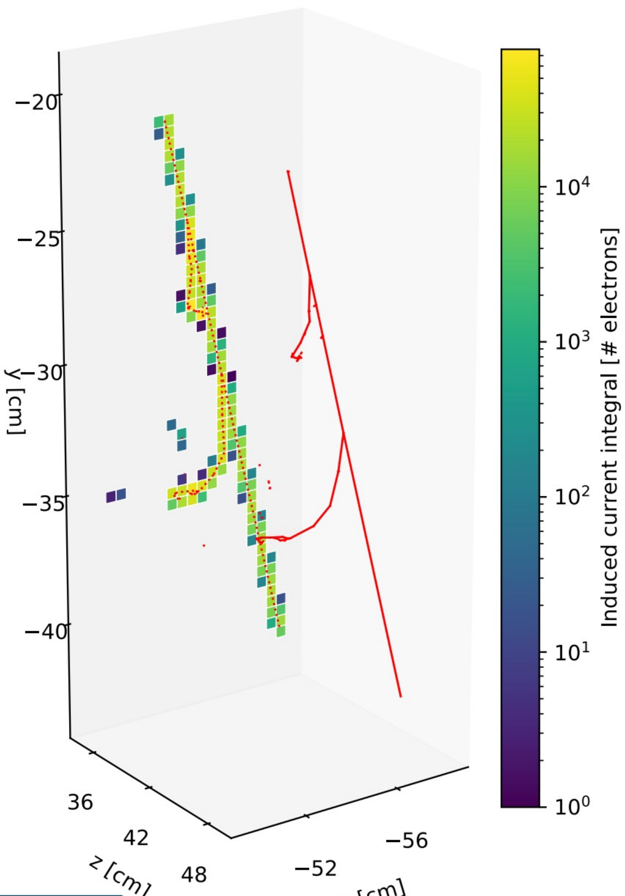
Geant4 visible energy depositions from a single spill at forward horn current and 1.2 MW beam power, where color indicates independent visible interactions

Simulation by B. Russell, LBNL

Pixel Charge Readout Simulation

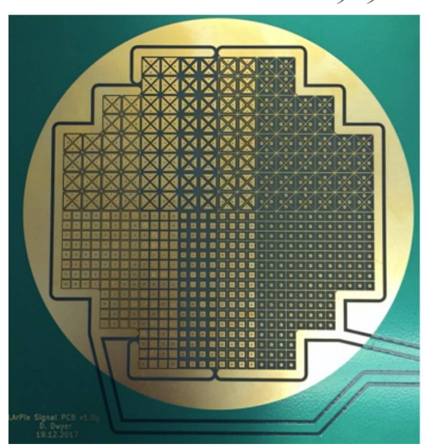
larnd-sim

3D event display of a simulated cosmic muon



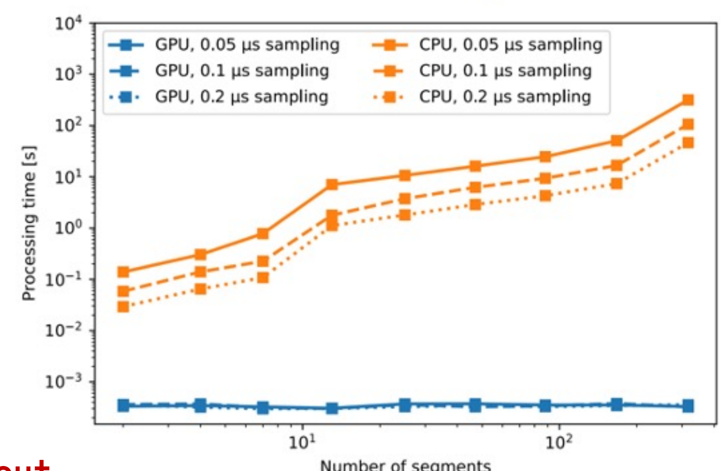
- Co-developed the simulation for DUNE LAr ND along with colleagues at Berkeley lab.
- A GPU compatible simulation ensures high-performance criteria required to meet the needs of massive event-rate environment and future proof the code.

LArPix – arXiv:1808.02969



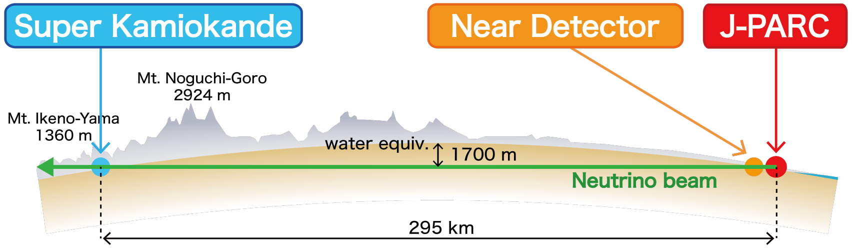
Pixelated charge readout

Performance comparison

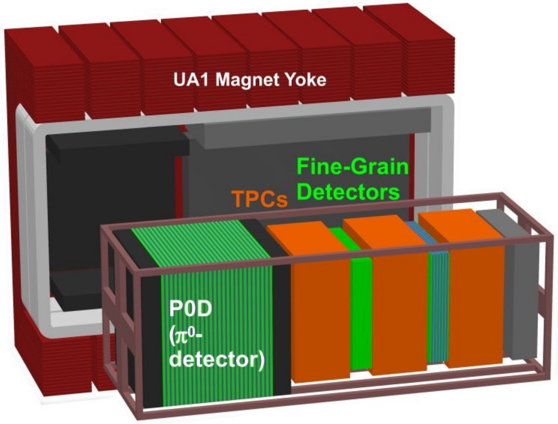


BERKELEY LAB

The T2K Detectors

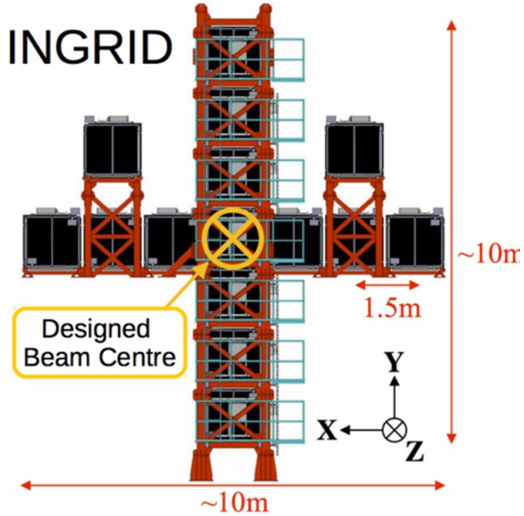


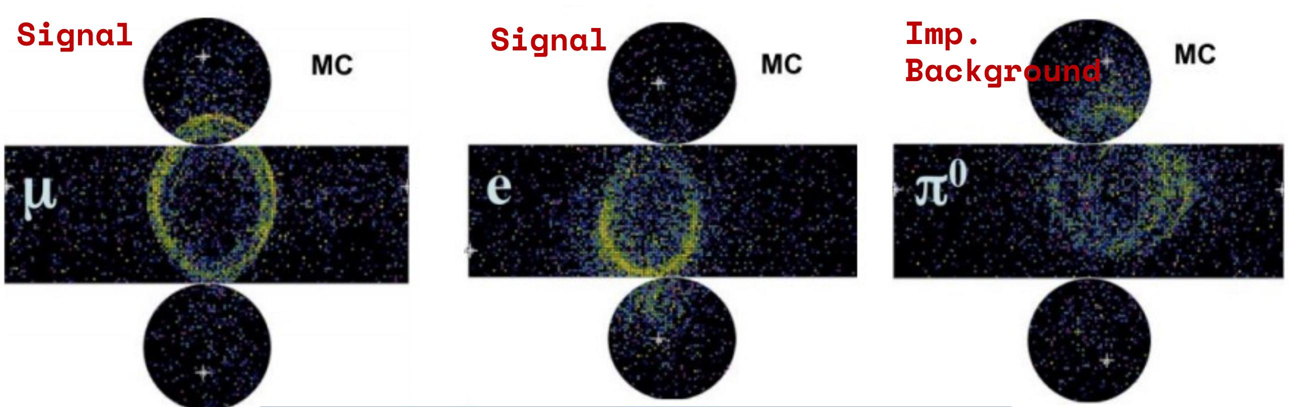
ND280 Off-axis detectors



- T2K's FD is Super-Kamiokande which is a water Cherenkov detector.
- T2K uses an **ensemble of scintillator and tracker detectors** both on-axis and and off-axis as its ND that is located at 280m from beam target.

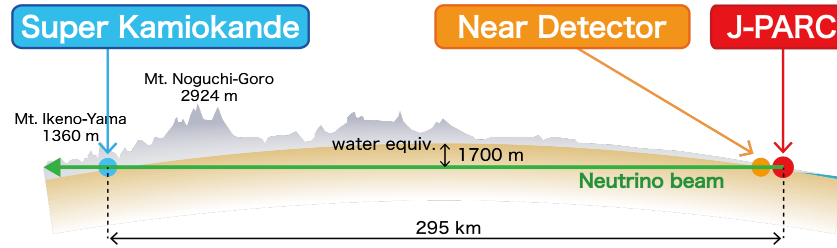
On-axis detector





Event Display at Super-Kamiokande

The T2K Detectors



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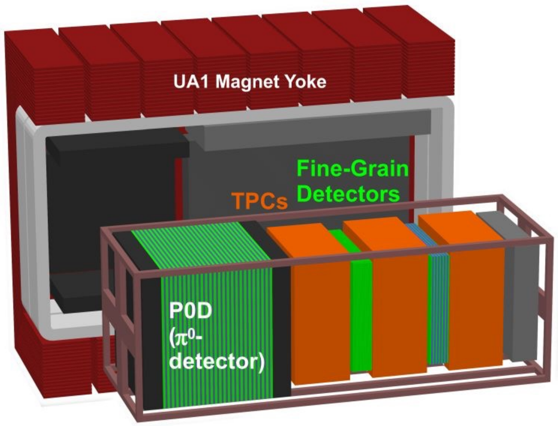

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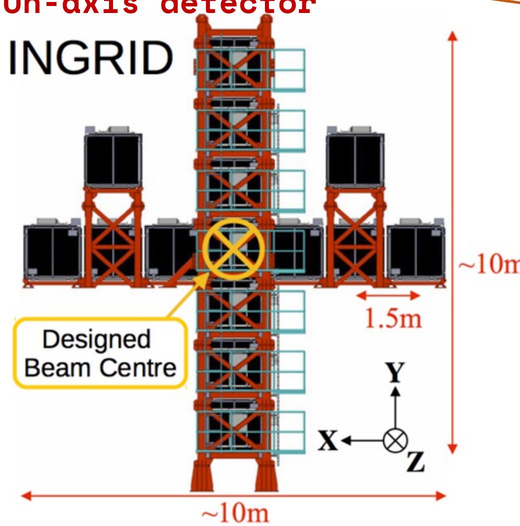
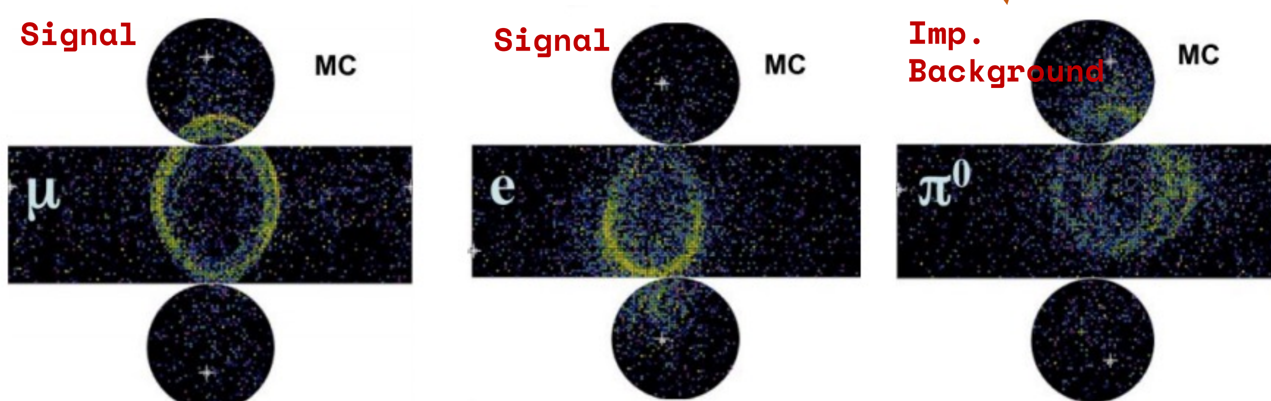
Measured Neutral-Current pion production cross-section at the T2K Near Detector.

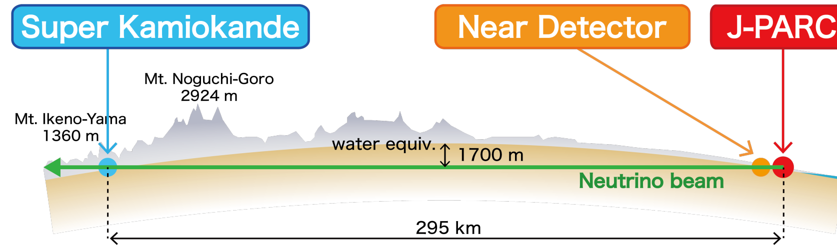
On-axis detector



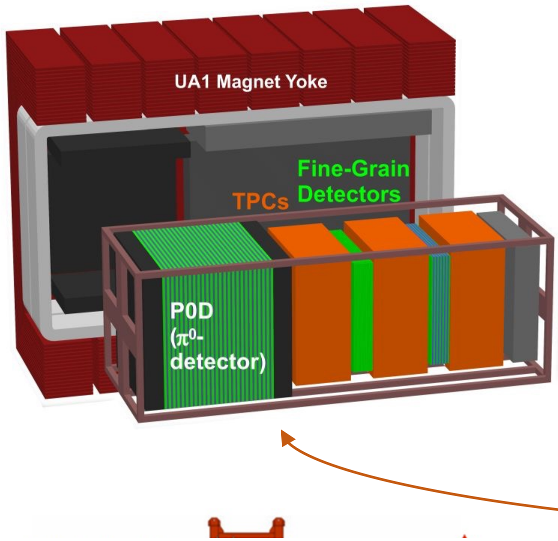


Event Display at Super-Kamiokande

The T2K Detectors



ND280 Off-axis detectors



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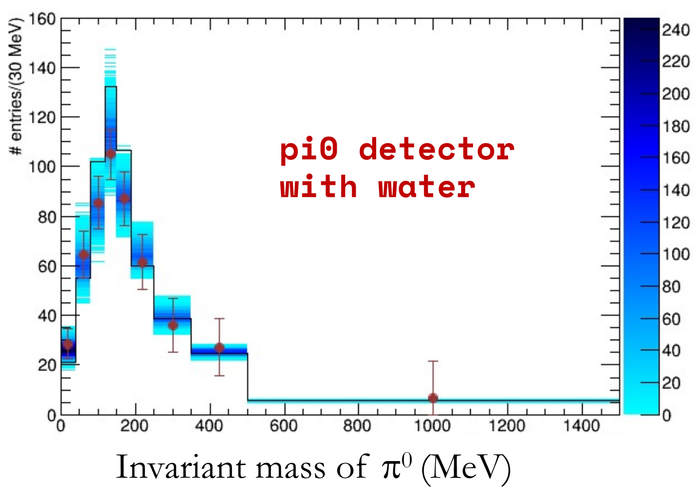
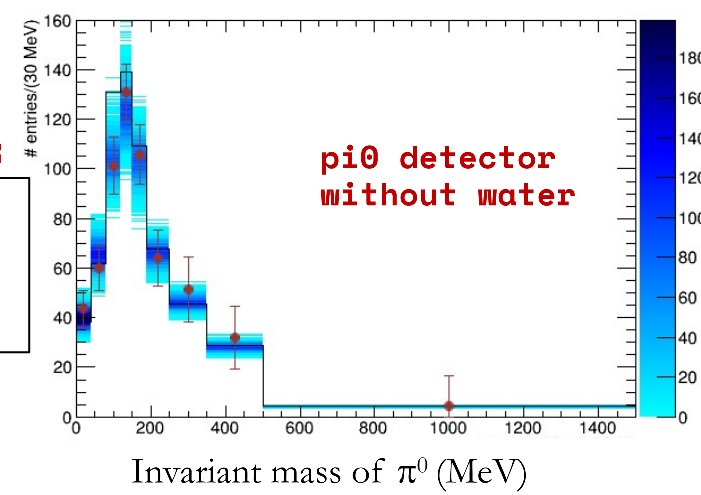


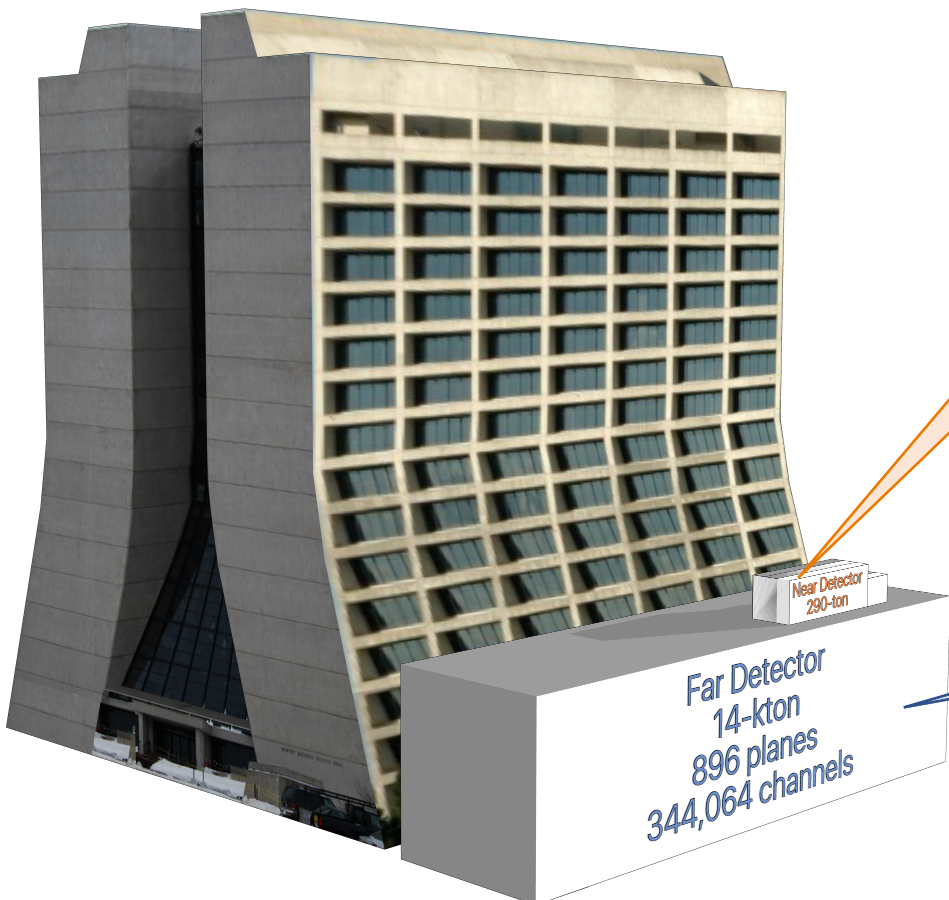
Event rate ON-WATER

Fit : 130 ± 20
MC : 167
Ratio : 0.78 ± 0.12

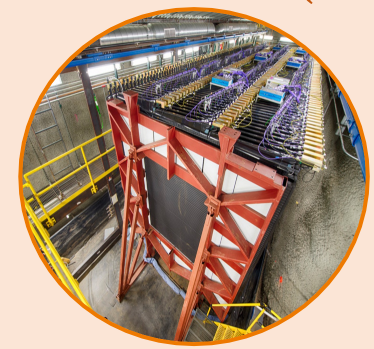


The NOvA Detectors

➢ NOvA deploys functionally identical detectors at ND and FD that only differ in size.



Near Detector (ND)



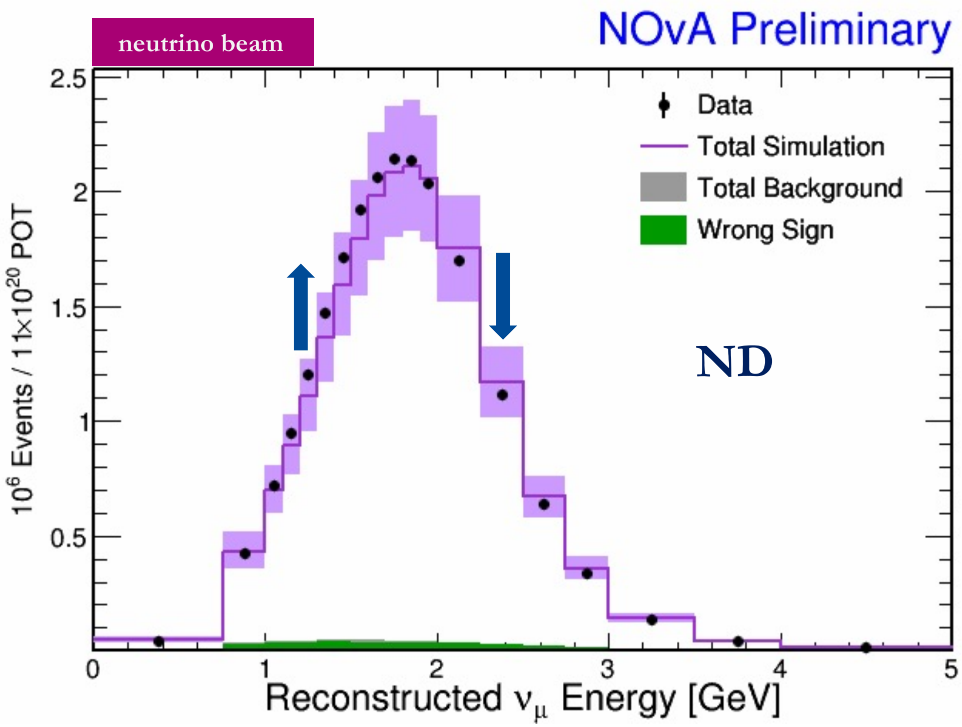
- 290-ton
- 1km from beam target

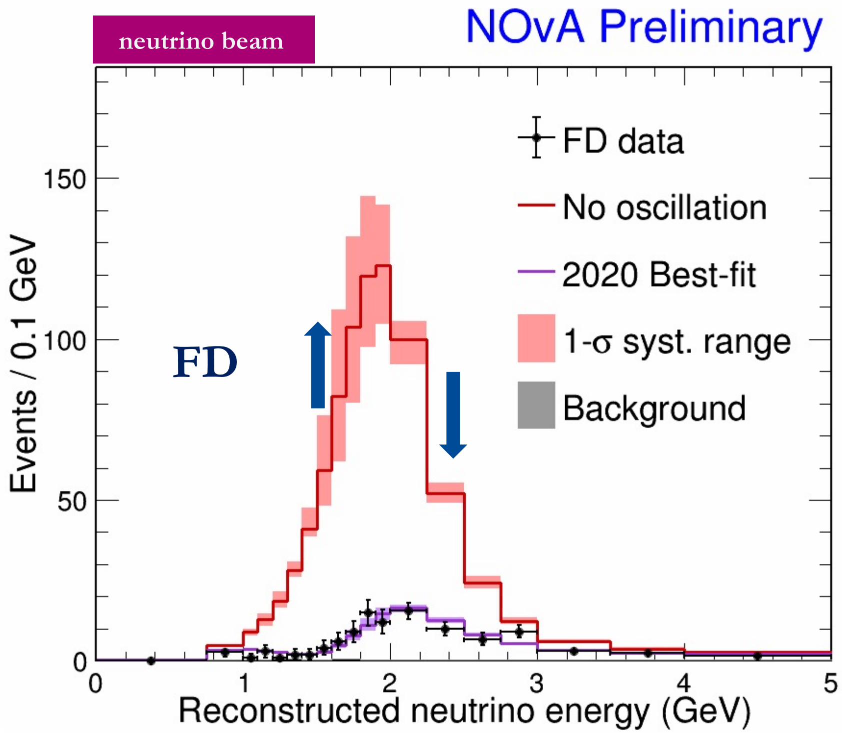
Far Detector (FD)

- 14-kton
- 810km from beam target

NOvA : ND Data Constraint

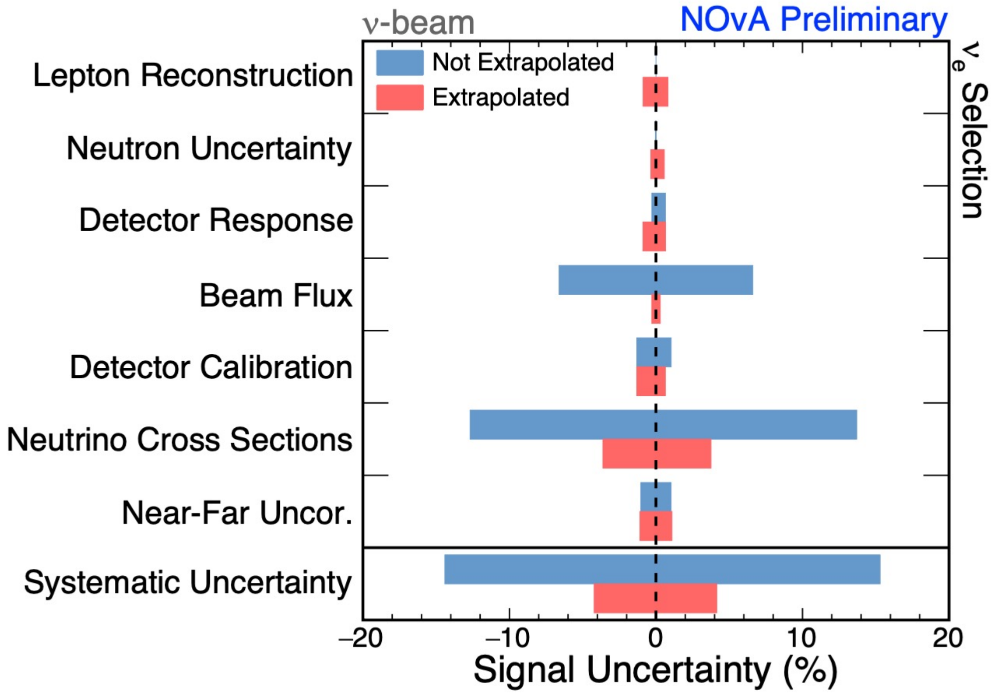
- A functionally identical ND provides a large cancelation in uncertainty.
- Difference in data-MC at ND is propagated to the FD simulation.





NOvA : ND Data Constraint

ND Data constrains the total systematic uncertainties in the FD prediction from >15% to ~5%.



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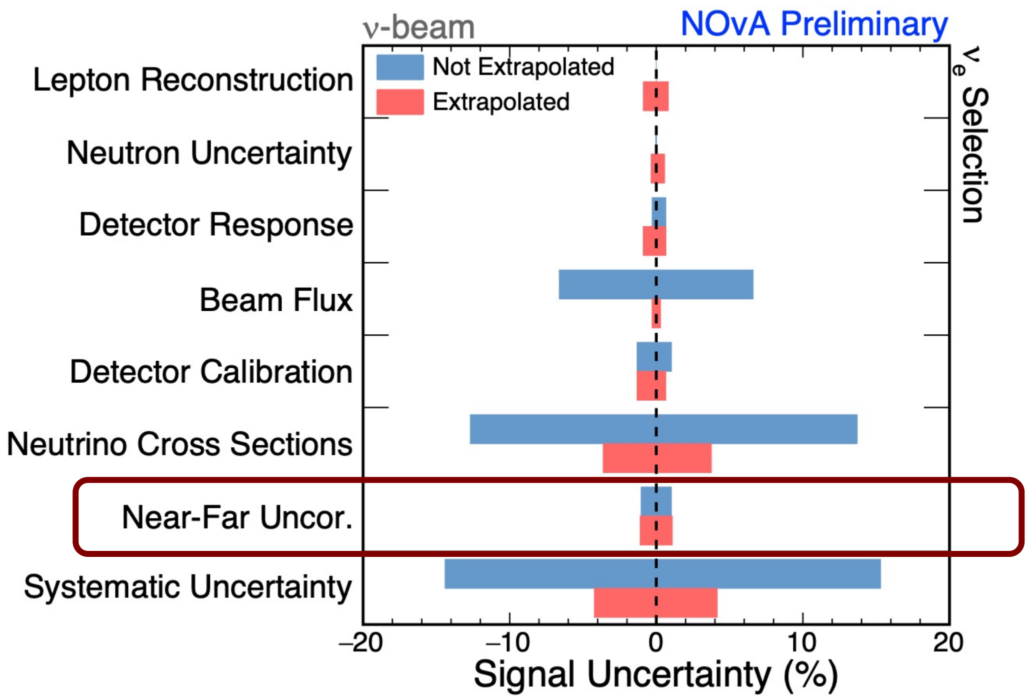
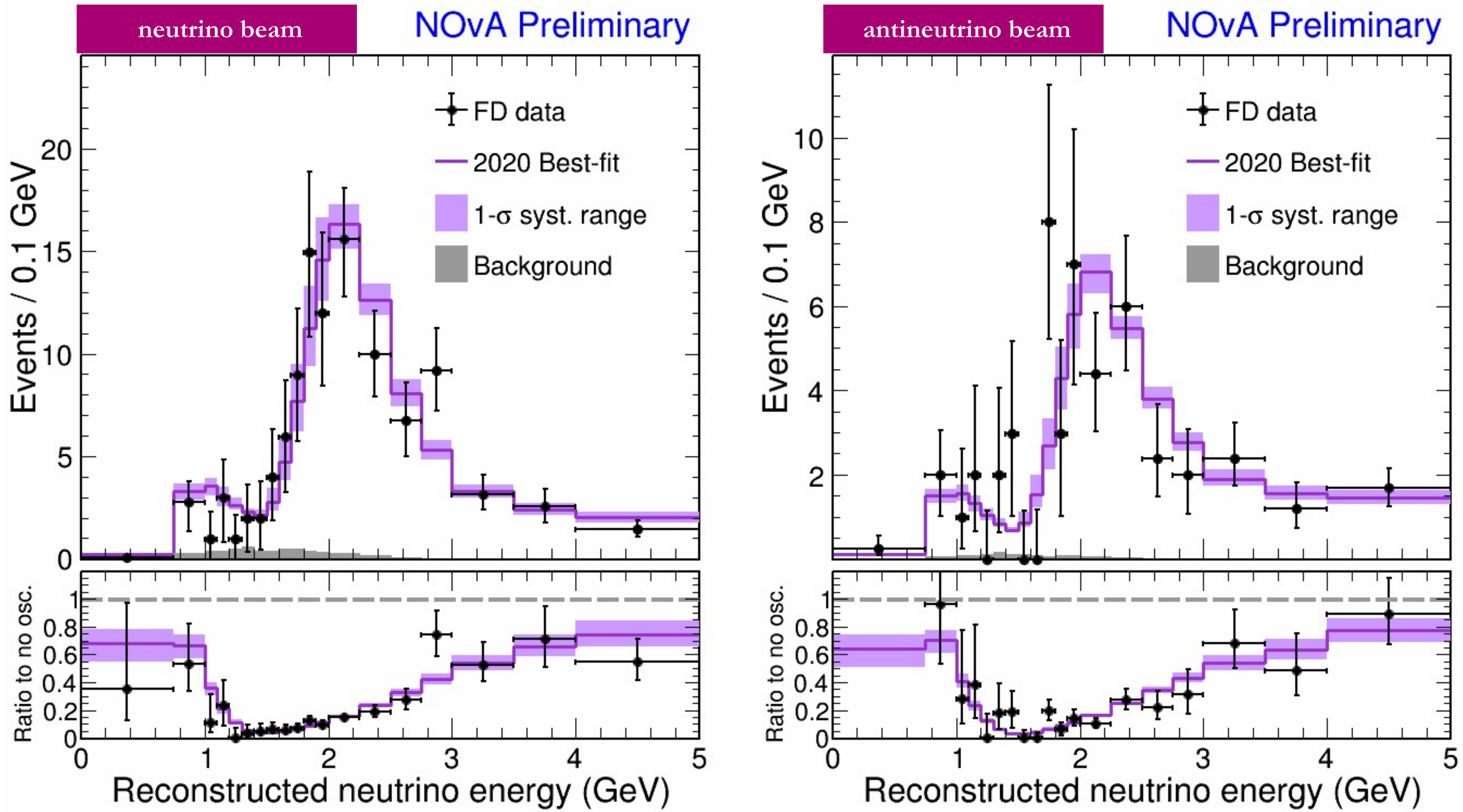


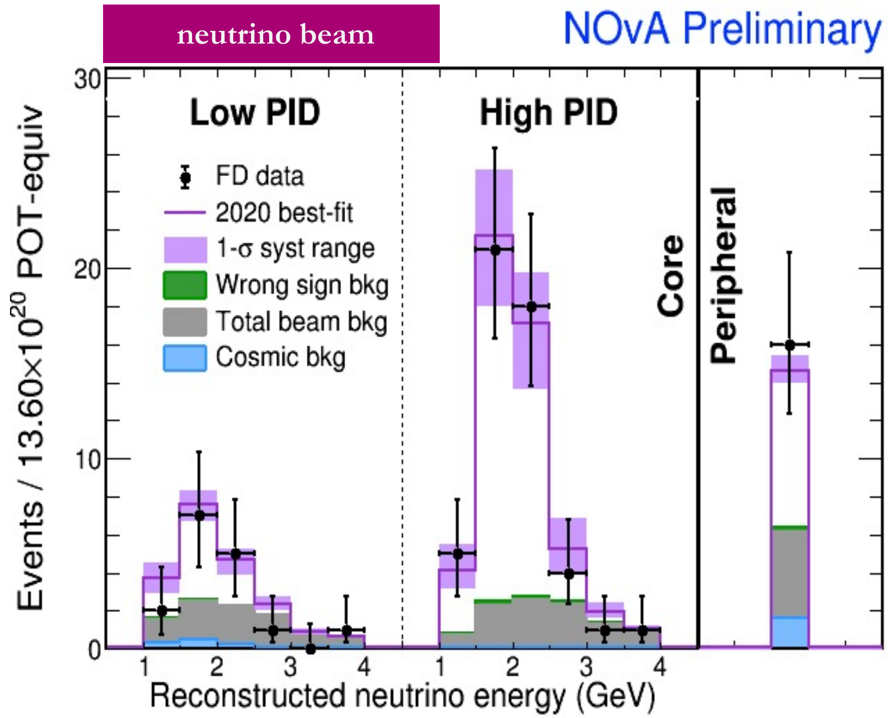
Implemented a robust calculation of systematics that are uncorrelated between ND and FD.

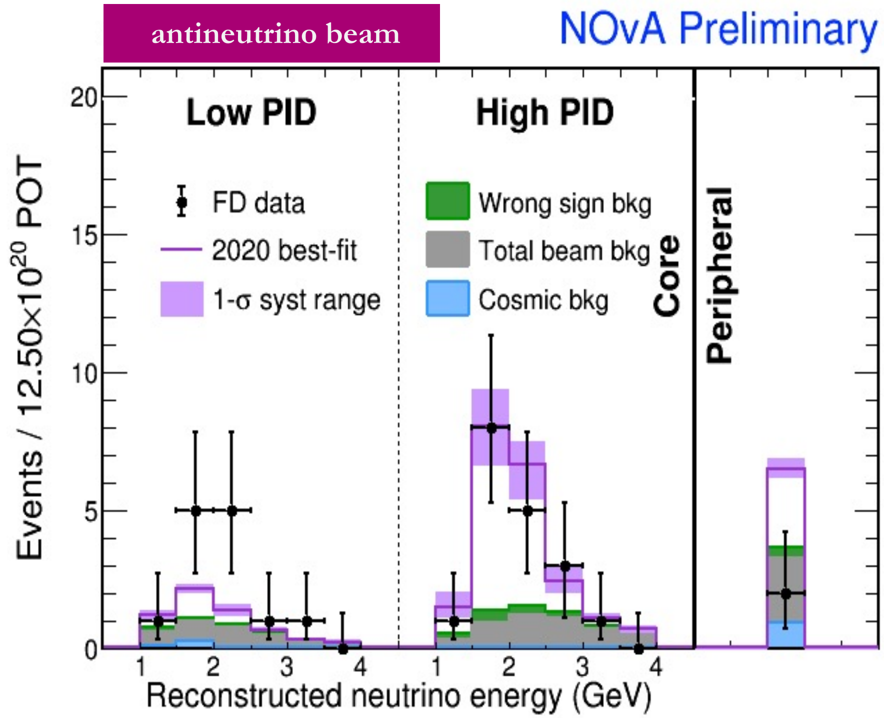
FD Data Samples : ν_μ disappearance



- The predictions (with the systematics band) are varied with the oscillation probabilities until the best-fit values with data are obtained.
- Applying 3-flavor oscillations describes these data well: p=0.705.

FD Data Samples : ν_e appearance





Observed 82 events (27 bkgd)

Observed 33 events (14 bkgd) : > 4σ $\overline{\nu}_e$ appearance

- Separating in bins of Particle ID enhances oscillation sensitivity which is dependent on a better rejection of background events.
- Peripheral sample include high PID events at the edges of the detector which might not be well contained.

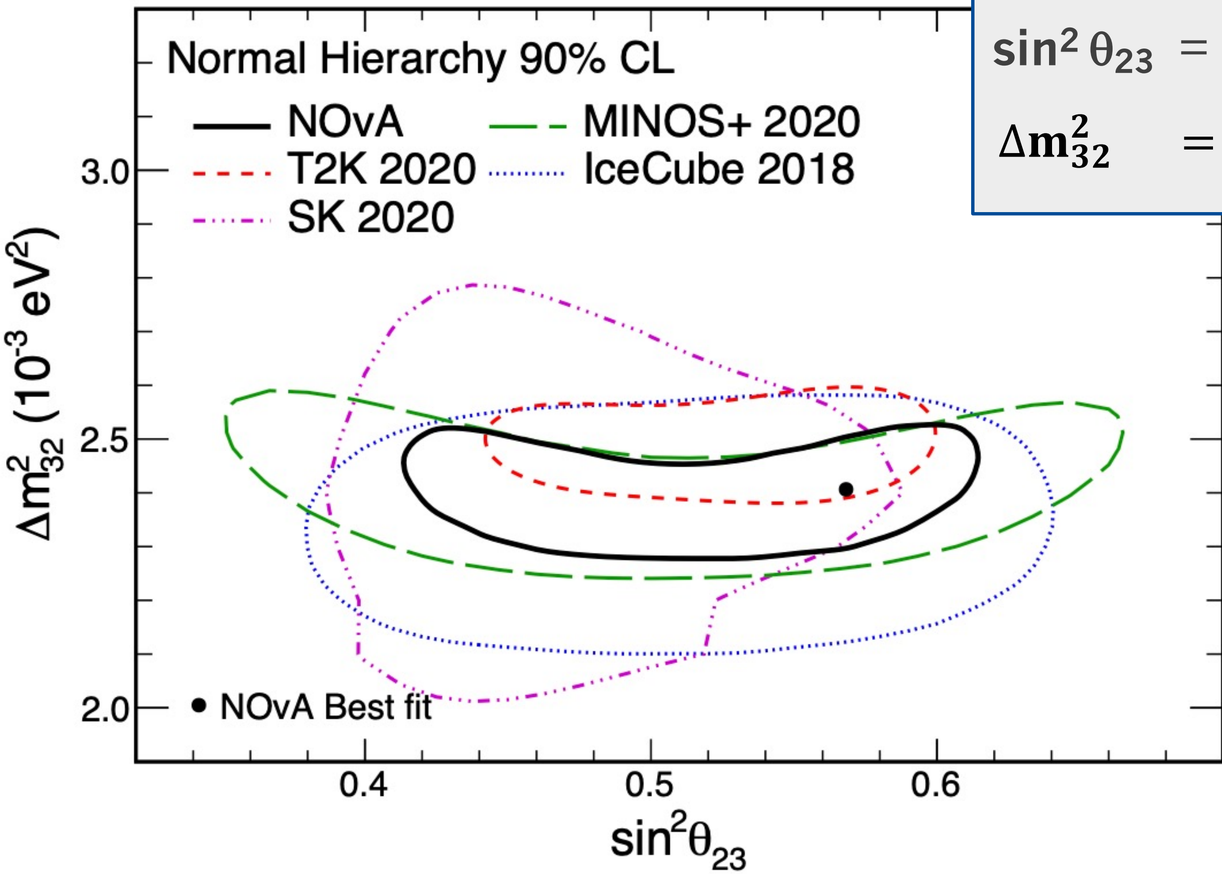
Extracting Oscillation Parameters

Best Fit:

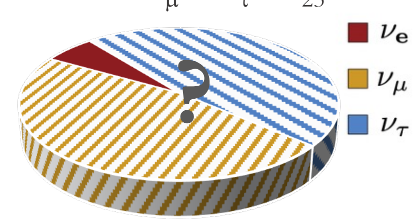
$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$

$\Delta m^2_{32} = (+2.41 \pm 0.07)\times 10^{-3}\ \mathrm{eV}^2$

~ 2.9% Precision

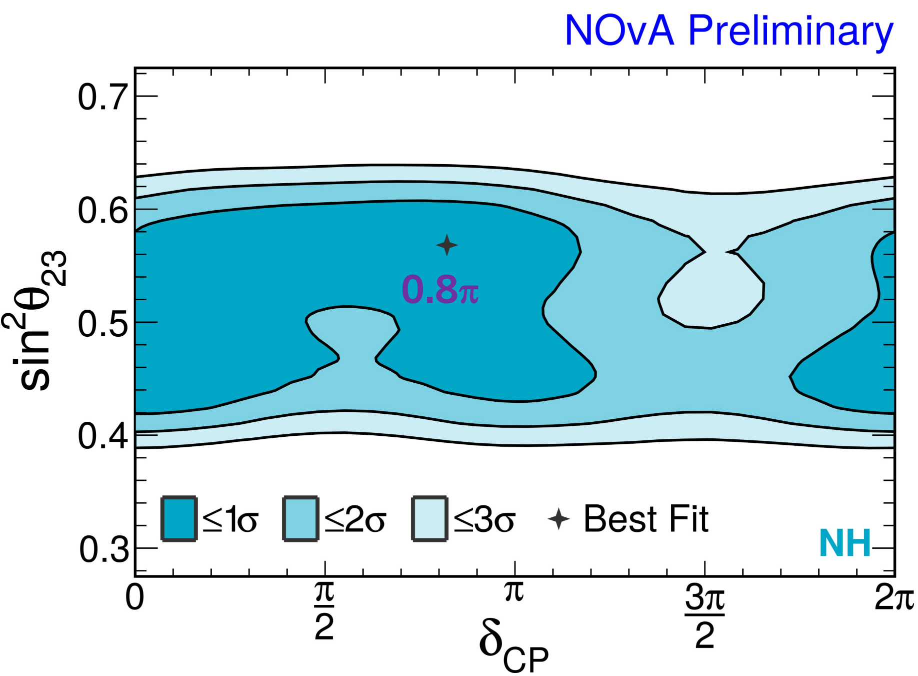


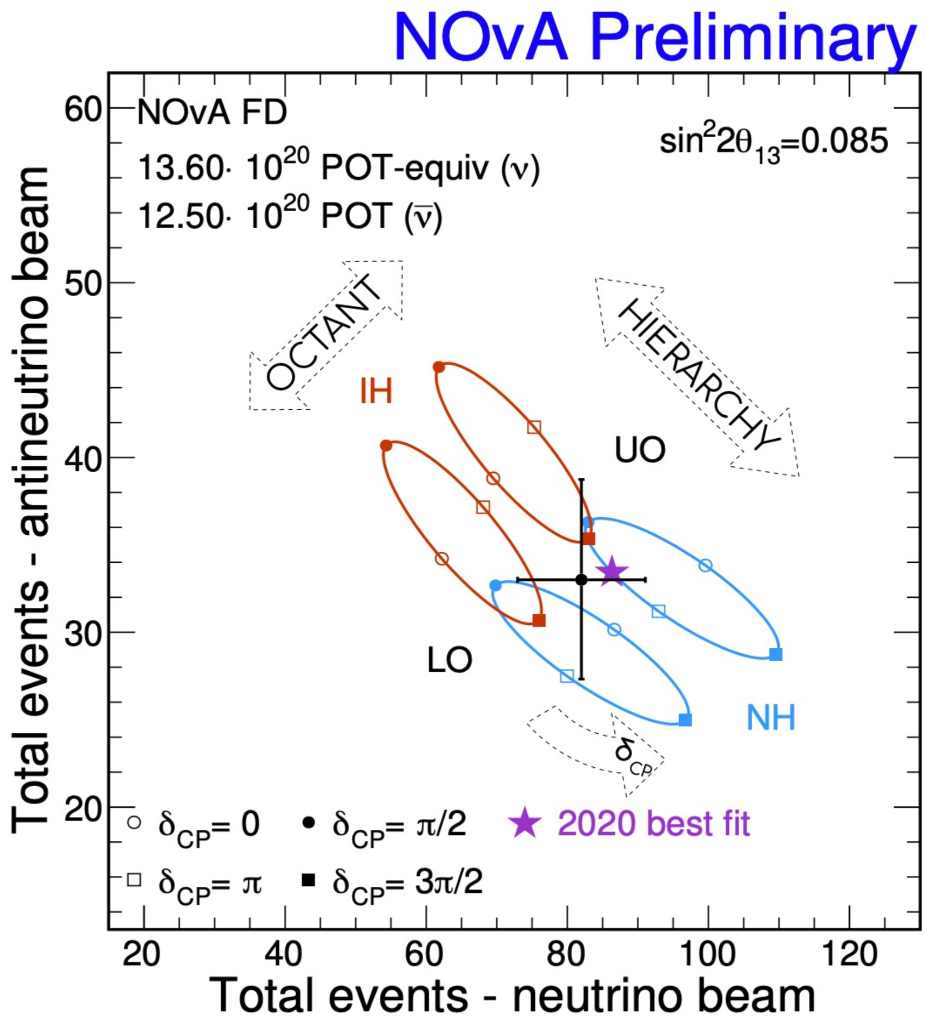
Is the amount of $\nu_\mu = \nu_\tau$? $\theta_{23} = 45^o$?



- **Maximal Mixing is disfavored at 1.1σ**
- Upper Octant is preferred at 1.2σ

δ_{CP} Measurement



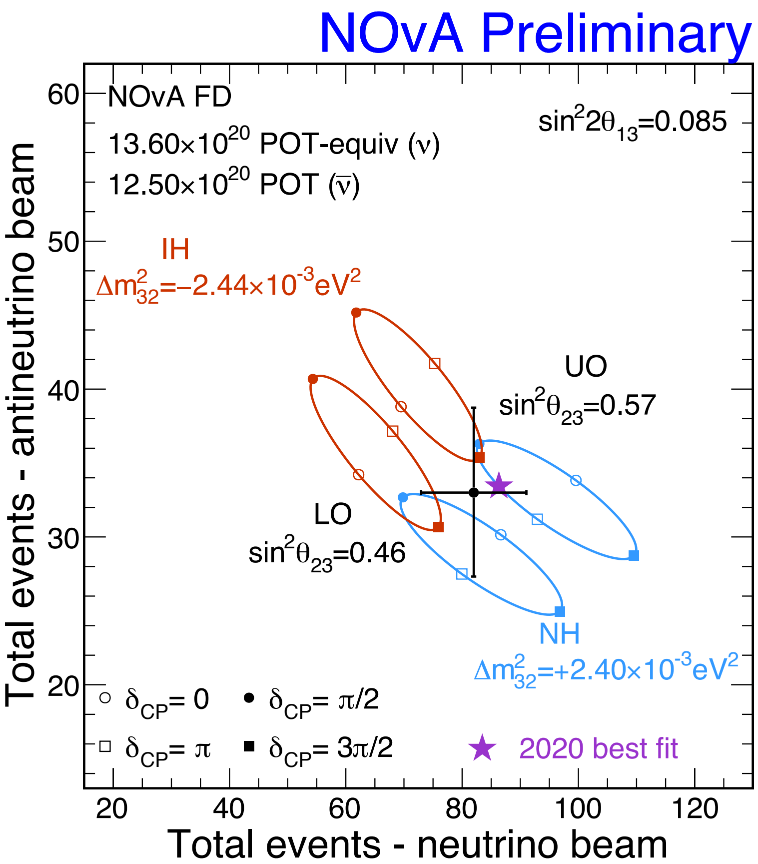


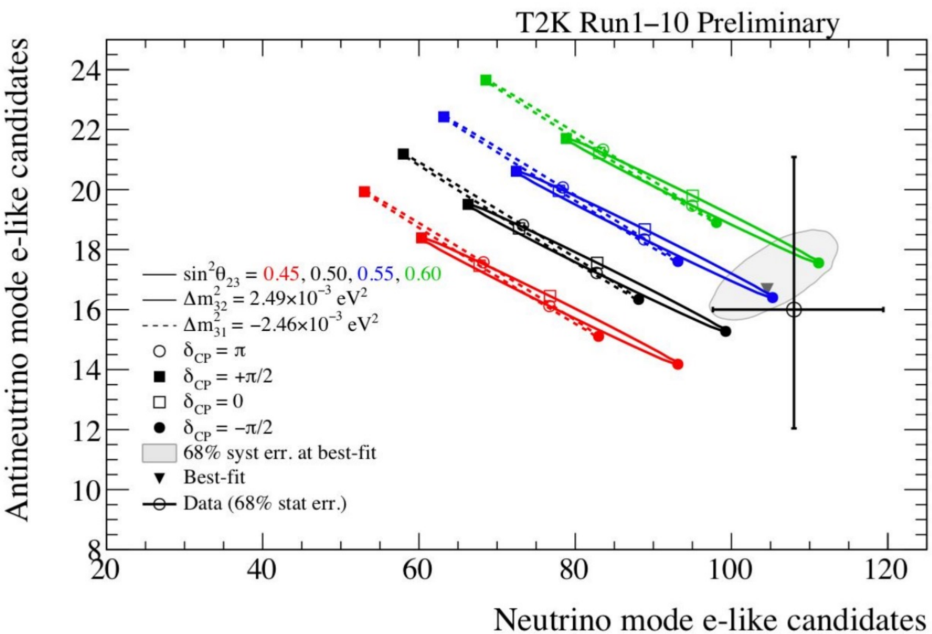
- Excludes {IH, $\delta_{CP} = \pi/2$ at > 3σ} & {NH, $\delta_{CP} = 3\pi/2$ at ~2σ}

- **Normal Ordering is preferred at 1.0σ**

Outlook for future:

NOvA and T2K



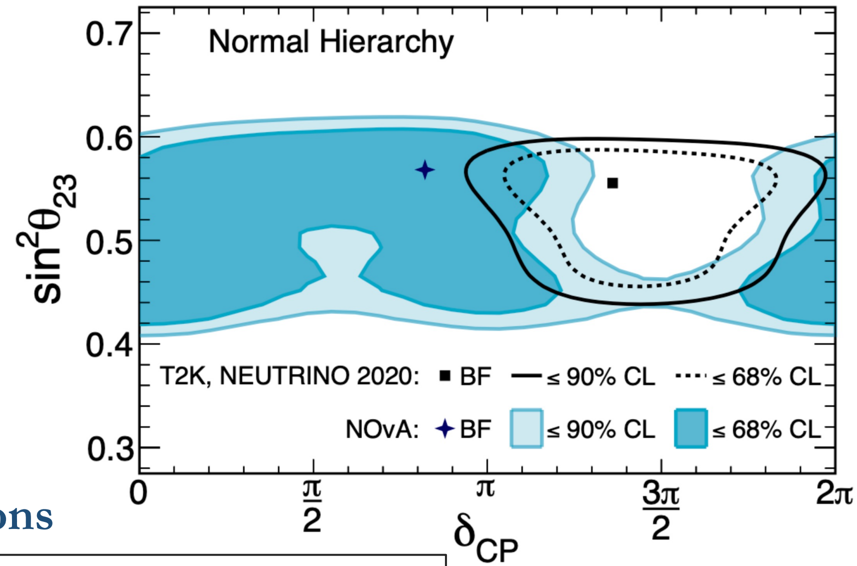


P. Dunne's talk at Neutrino 2020

- T2K sees an asymmetry in their ν_e and $\overline{\nu}_e$ appearance and their best fit is consistent with large CP violation for Normal Hierarchy.

NOvA and T2K

- Latest results from the two experiments have generated a lot of excitement in the community.



- ## Non-standard Interactions

CP-Violating Neutrino Non-Standard Interactions in Long-Baseline-Accelerator Data

Peter B. Denton,[1,*] Julia Gehrlein,[1,†] and Rebekah Pestes[1,2,‡]

Non-standard neutrino interactions as a solution to the NOνA and T2K discrepancy

Sabya Sachi Chatterjee[1,*] and Antonio Palazzo[2,3,†]

- ## Global preference for Inverted Hierarchy

Back to (Mass-)Square(d) One: The Neutrino Mass Ordering in Light of Recent Data

Kevin J. Kelly,[1,*] Pedro A. N. Machado,[1,†] Stephen J. Parke,[1,‡]
Yuber F. Perez-Gonzalez,[1,2,3,§] and Renata Zukanovich Funchal[4,¶]

The fate of hints: updated global analysis of three-flavor neutrino oscillations [NuFit 5.0]

Ivan Esteban,[a] M. C. Gonzalez-Garcia,[a,b,c] Michele Maltoni,[d] Thomas Schwetz,[e] Albert Zhou[e]

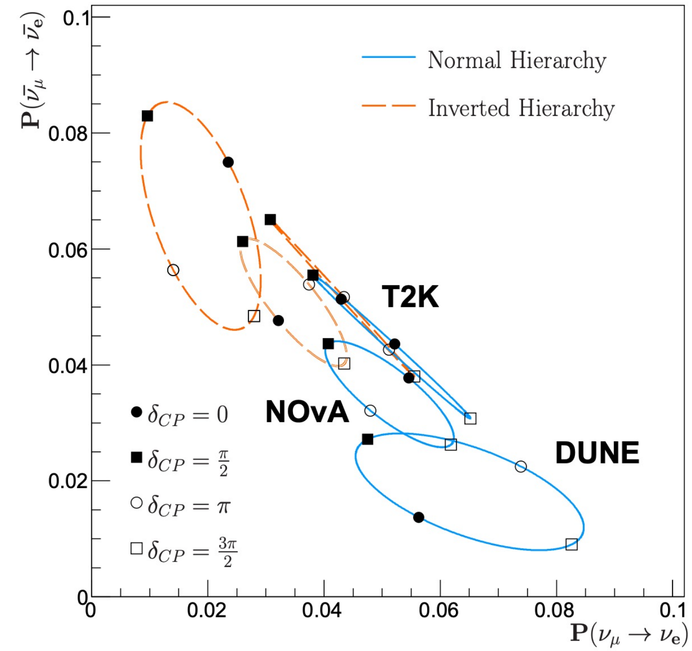
- ## Energy-dependent parameters

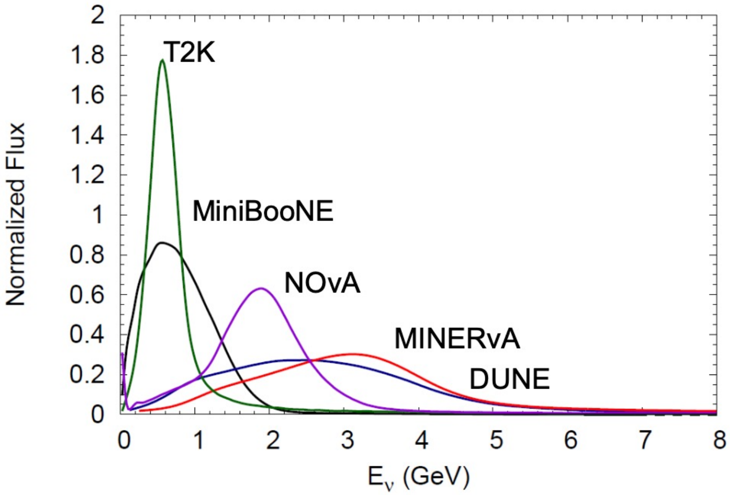
Energy-Dependent Neutrino Mixing Parameters at Oscillation Experiments

K. S. Babu,[1] Vedran Brdar,[2,3] André de Gouvêa,[2] and Pedro A. N. Machado[3]

NOvA - T2K : Complementarity

- NOvA's longer baseline (810 km) as compared to T2K (295 km) sees larger matter effects and has greater sensitivity to mass hierarchy.
- T2K (0.6 GeV peak) is mostly dominated by CCQE (and MEC) events while NOvA's (2 GeV peak) beam energy has a much larger component of RES and DIS events.
- NOvA and T2K use distinct methods to estimate neutrino energy and different approaches to incorporate Near Detector data to constrain systematics.





NOvA – T2K Joint Fit

- An agreement was signed between the two experiments to share data and collaborate on a joint-analysis.
- The joint analysis would entail:
  - A fully self-consistent joint fit would use the complete likelihood of both experiments with appropriate statistical method.
  - A detailed understanding of neutrino interaction models used by the two experiment. These can be reconciled with suitable energy scaling when needed.
  - Correlating systematics that have a similar impact on both experiment.

Projected timescale for the first result - * 2022 *

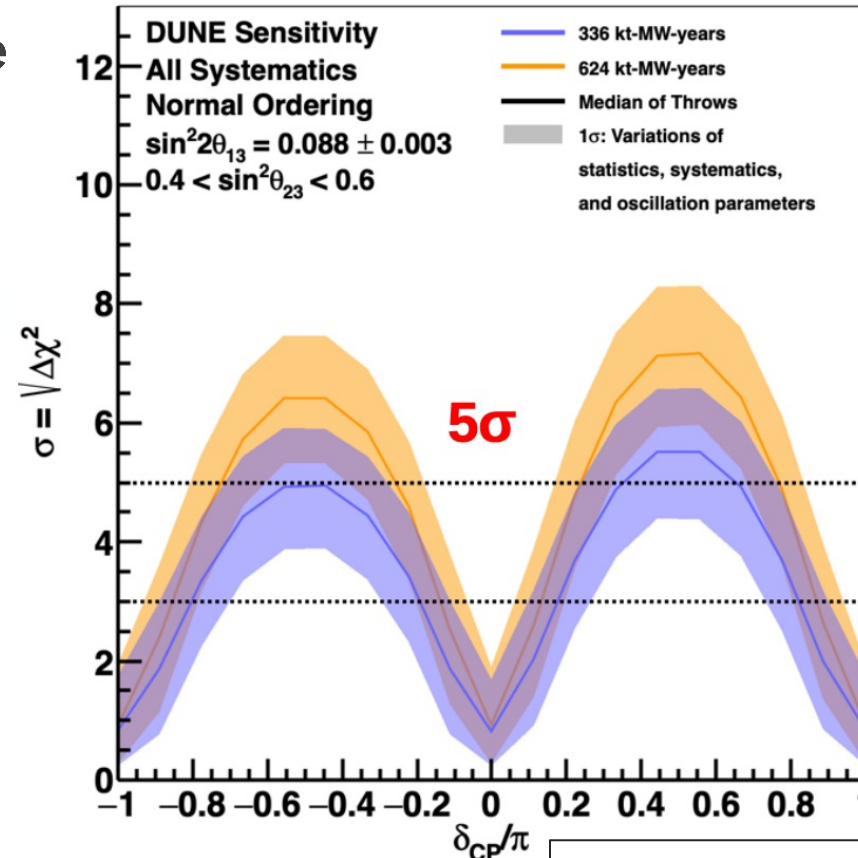
Conclusion - I

- Long-baseline neutrino oscillations experiments are poised to answer some of the long-standing puzzles in the neutrino sector.
- NOvA data disfavors asymmetry between ν_e and $\bar{\nu}_e$ appearance while T2K sees an asymmetry and their best fit is consistent with maximal CP violation.
- **NOvA-T2K joint analysis** is converging rapidly and is on-track to report first measurements in 2022.

Conclusion - II

- **DUNE will push neutrinos in the precision era and would be able to make a definitive measurement of neutrino oscillation parameters.**

- DUNE will be able to determine the Mass Ordering soon after it starts taking data (12kt-MW-yr*) and a likely determination of 3σ (5σ) for 50% δ_{CP} values after 197 (646) kt-MW-yr.



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$$\Delta\chi^2 = \chi^2_{0,\pi} - \chi^2_{\mathrm{CPV}}$$

*The sensitivities are quoted in kt-MW-year exposures rather than yearly timeline to avoid dependence on module construction and beam schedules.

It takes a (global) village . . .

Thank you!

Supplementary Slides

Oscillation Analysis Strategy

1. **Monte Carlo Simulations**
   - Generate neutrino flux, neutrino interaction and propagate it through the detector.
   - Simulate detector response to the resulting charged particle and produced light.

2. **ND Data-Driven Constraints on simulation**
   - The ND provides valuable constrains on the uncertainty in flux, neutrino interaction models and detector response systematics.

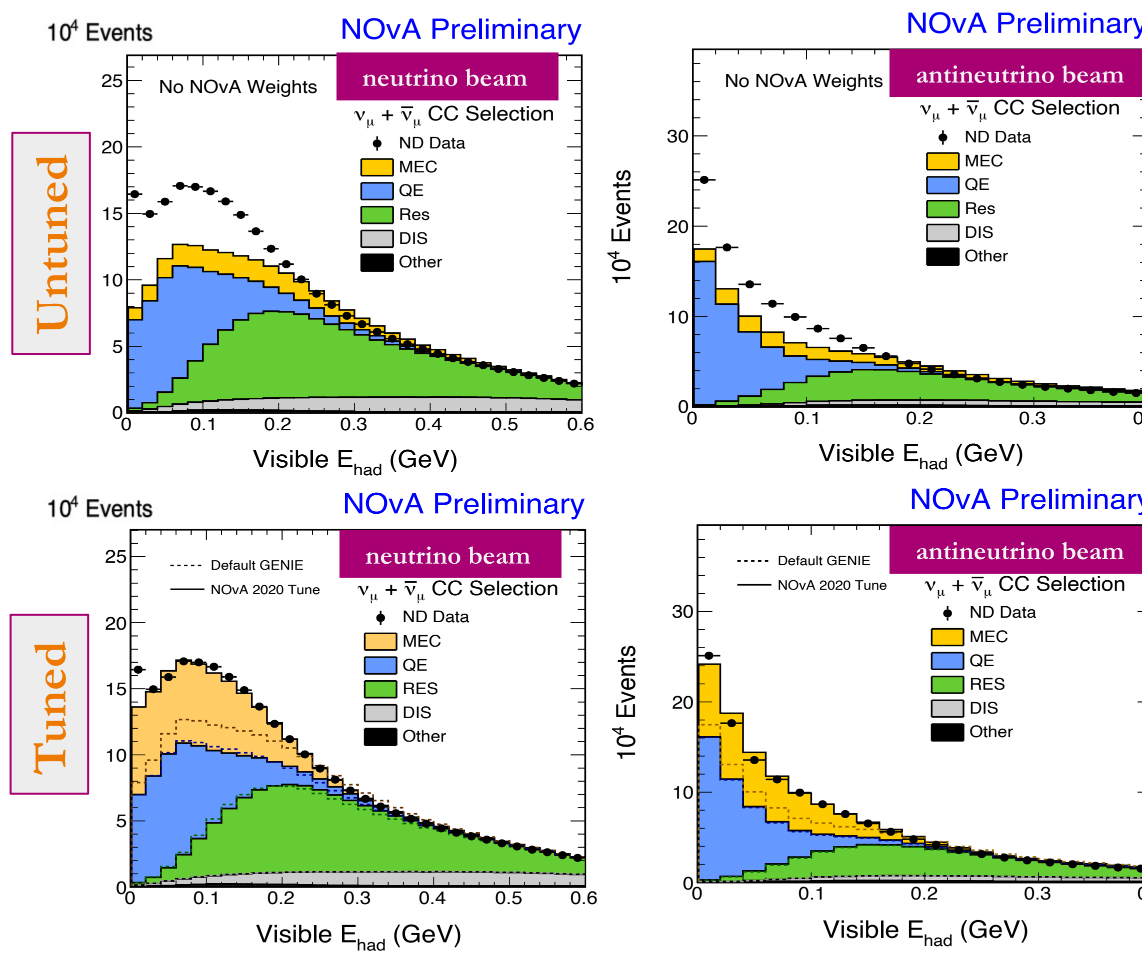
3. **Comparison with FD data**
   - ND constraints are propagated to the FD simulation and compared with ν_μ and ν_e interaction datasets.

4. **Extracting Oscillation Parameters**
   - Oscillation parameters are varied to fit the ν_μ disappearance and ν_e appearance in both the neutrino and antineutrino beam mode simultaneously.

The ND and FD data can be fit simultaneously.

NOvA ND Tune

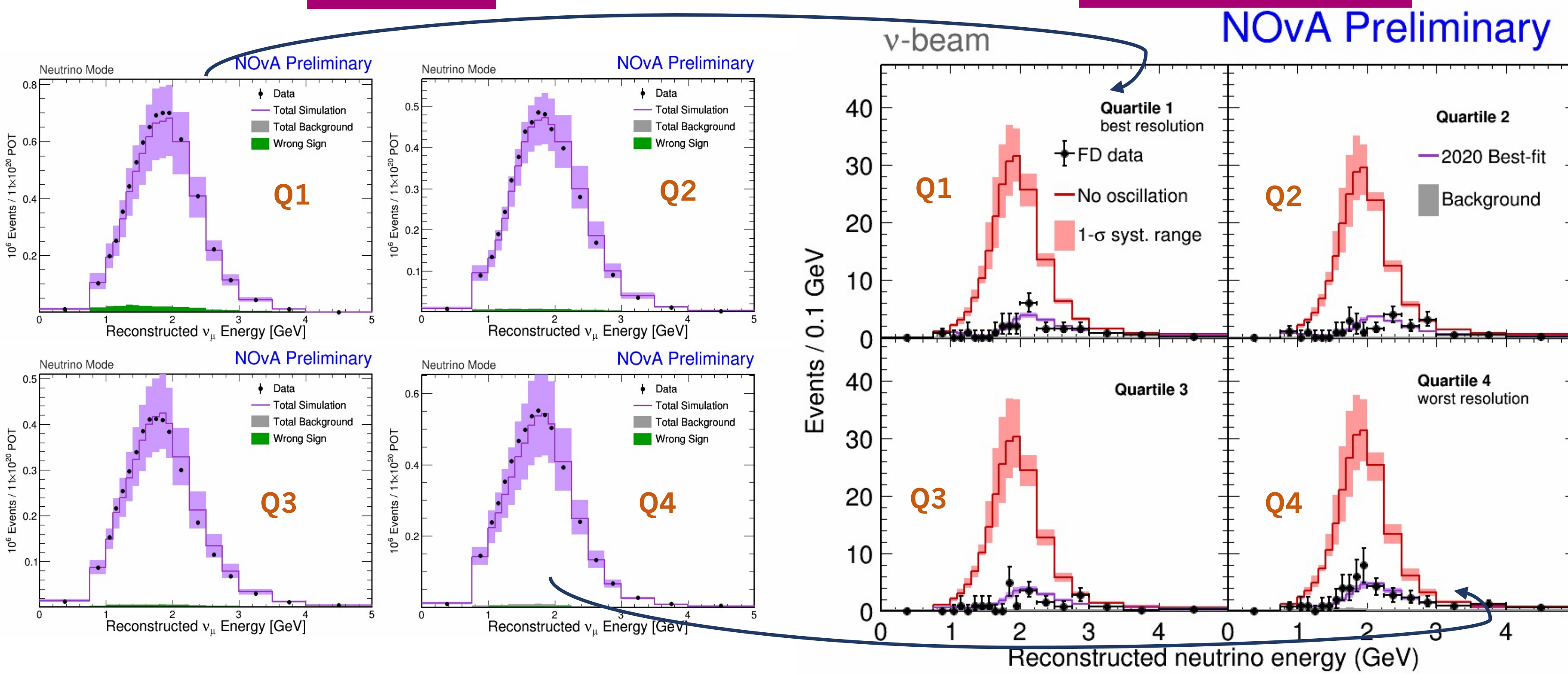
- We use **GENIE**(v3.0.6) for neutrino interaction generation.
- Nuclear effects are still not well-modeled. Out-of-the-box GENIE does not describe ND data well.
- Tuned GENIE by varying the MEC and FSI components.
- Any remaining differences between data and MC are covered by systematic uncertainty band and are extrapolated to FD Simulation as ND Data Constraints.



ND Data Constraint : Energy Resolution

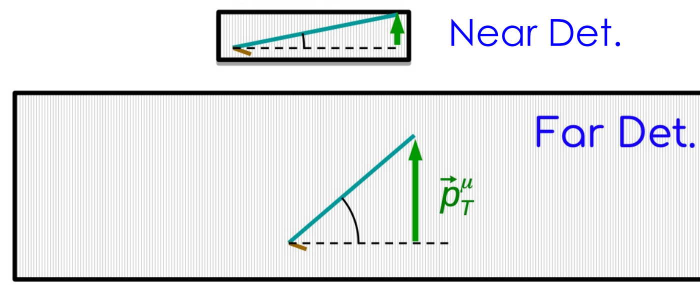
- Oscillation sensitivity for ν_μ disappearance measurement depends on the shape of the spectrum.
- Dividing the ν_μ sample in quartiles (Q1-Q4) of fraction of hadronic energy separates high-resolution events. This increases the sensitivity to the shape of the oscillation dip.

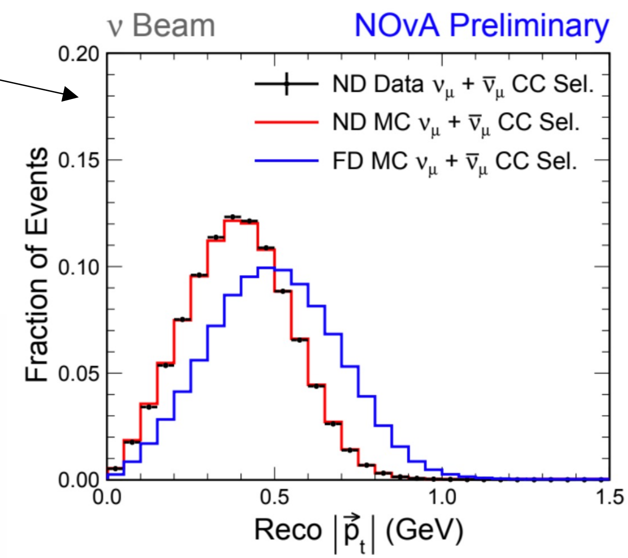
ND DATA **FD PREDICTION**

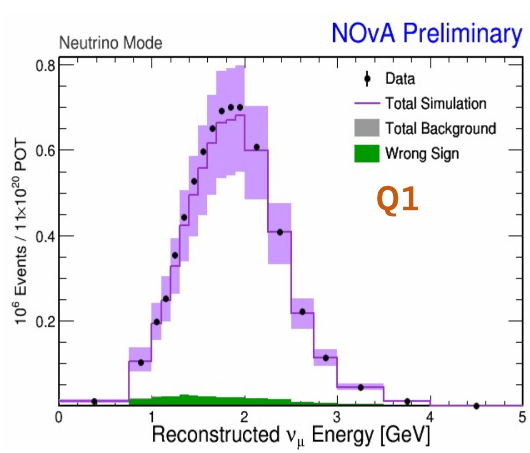


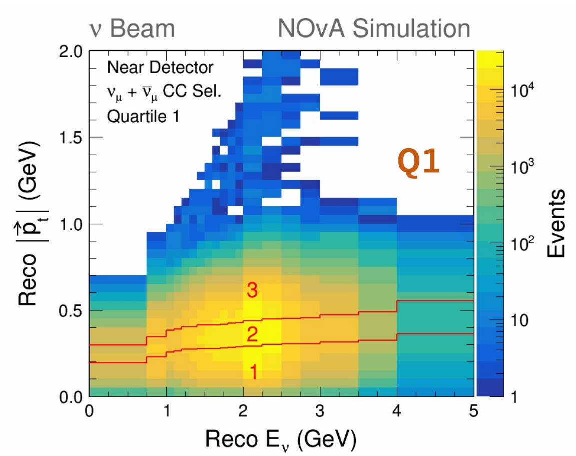
ND Data Constraint : Detector Acceptance

- Due to a large difference in size of the detector, FD has a larger acceptance of the particles going in the transverse direction than the ND.
- This difference can be seen in the lepton $|\vec{p_t}|$ distributions.
- **Sub-divide the sample in 3 bins of lepton $|\vec{p_t}|$** to better match the samples applying the constraint between the two detectors.

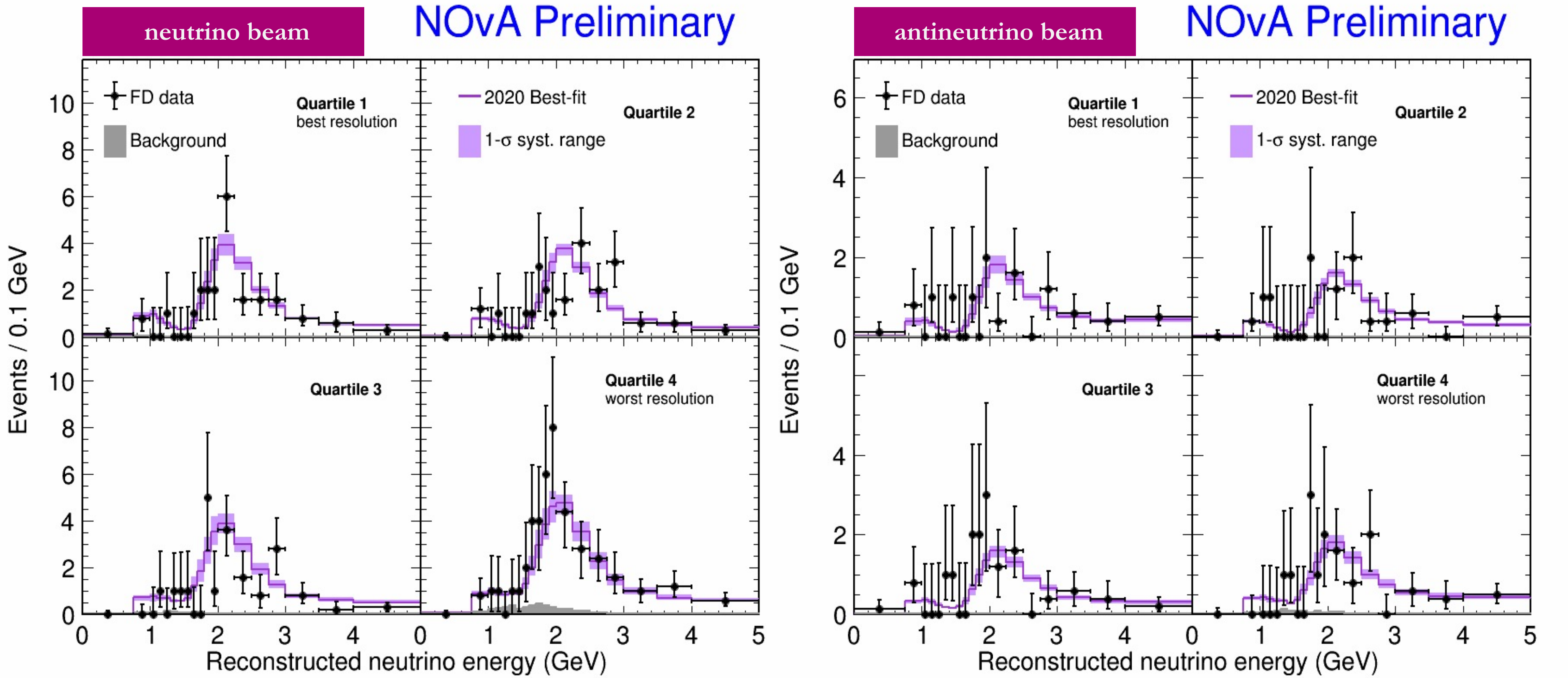








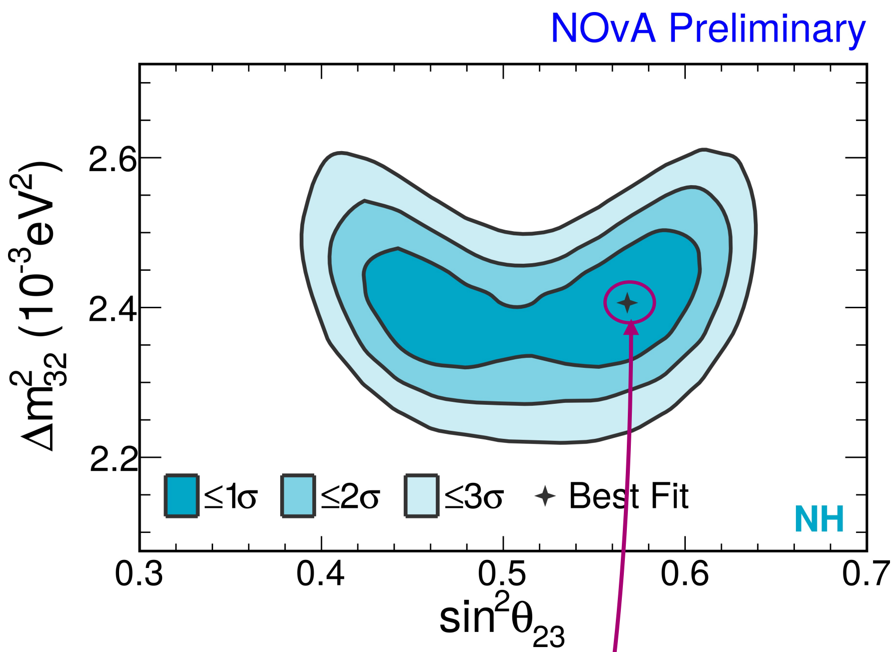
FD Data Samples : ν_μ disappearance

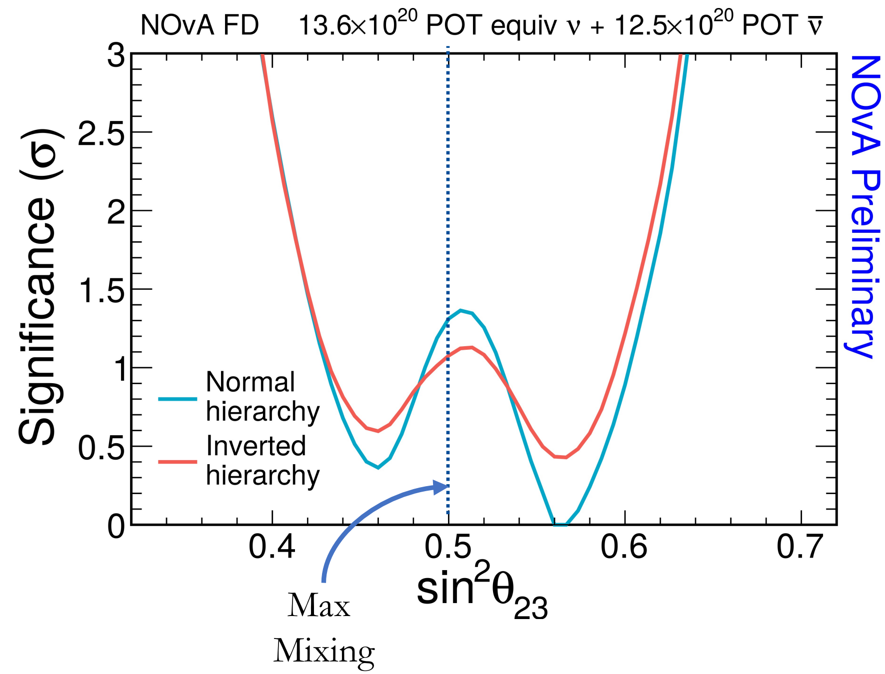


- The predictions (with the systematics band) are varied with the oscillation probabilities until the best-fit values with data are obtained.
- Applying 3-flavor oscillations describes these data well: p=0.705.

Extracting Oscillation Parameters

Oscillation parameters are extracted by a simultaneous joint fit of both datasets in neutrino and antineutrino mode.





Best Fit:

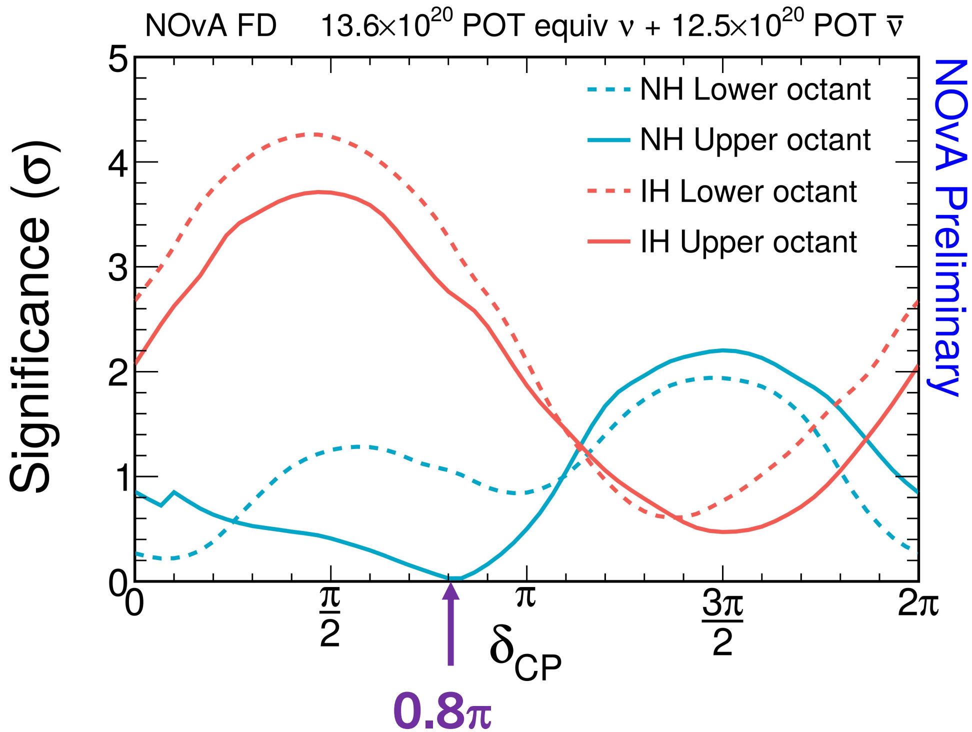
$$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$$

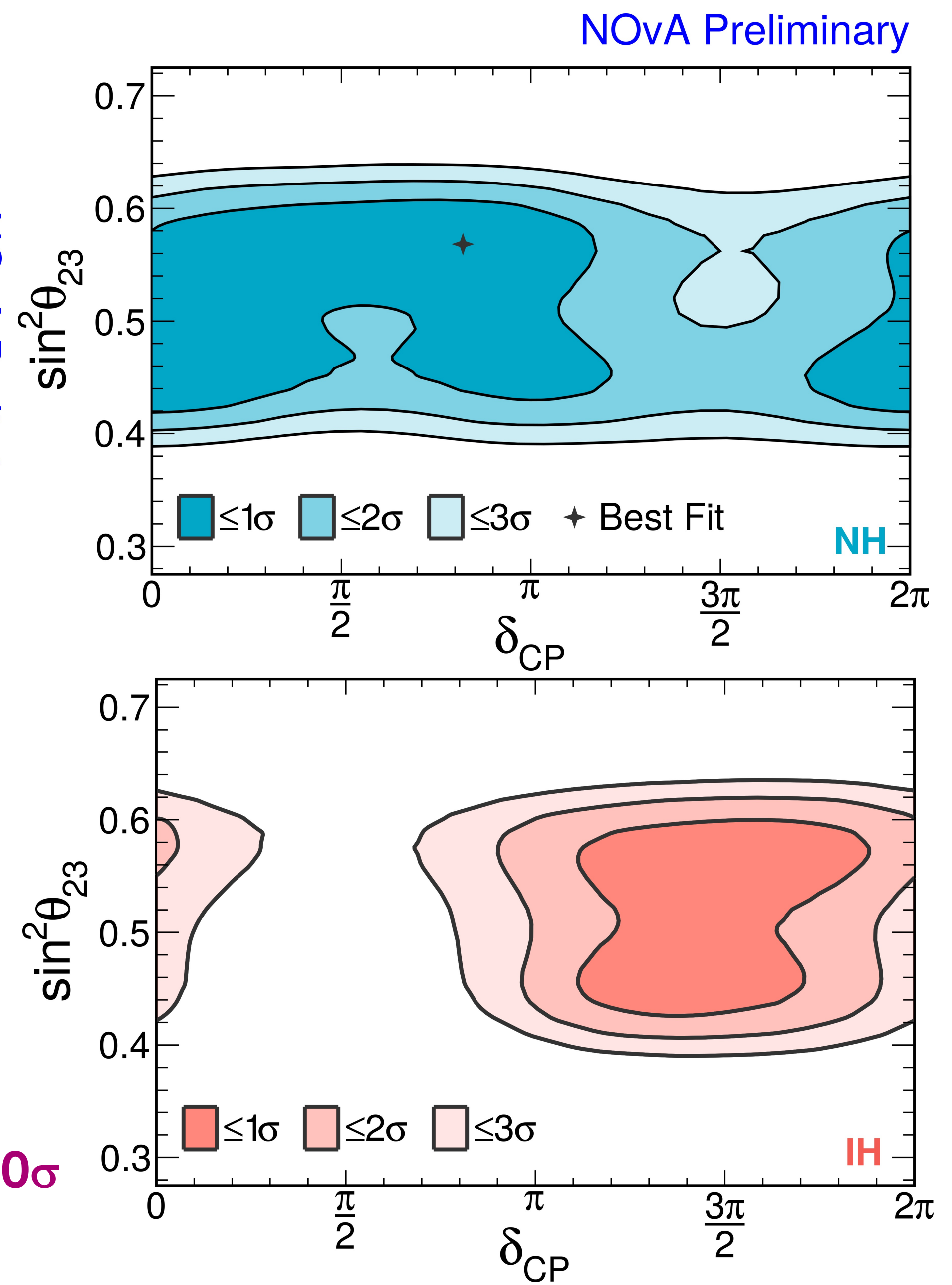
$$\Delta m^2_{32} = (+2.41 \pm 0.07)\times 10^{-3}\ \mathrm{eV}^2$$

~ 2.9% Precision

- Maximal Mixing is disfavored at 1.1σ
- Upper Octant is preferred at 1.2σ

δ_{CP} Measurement

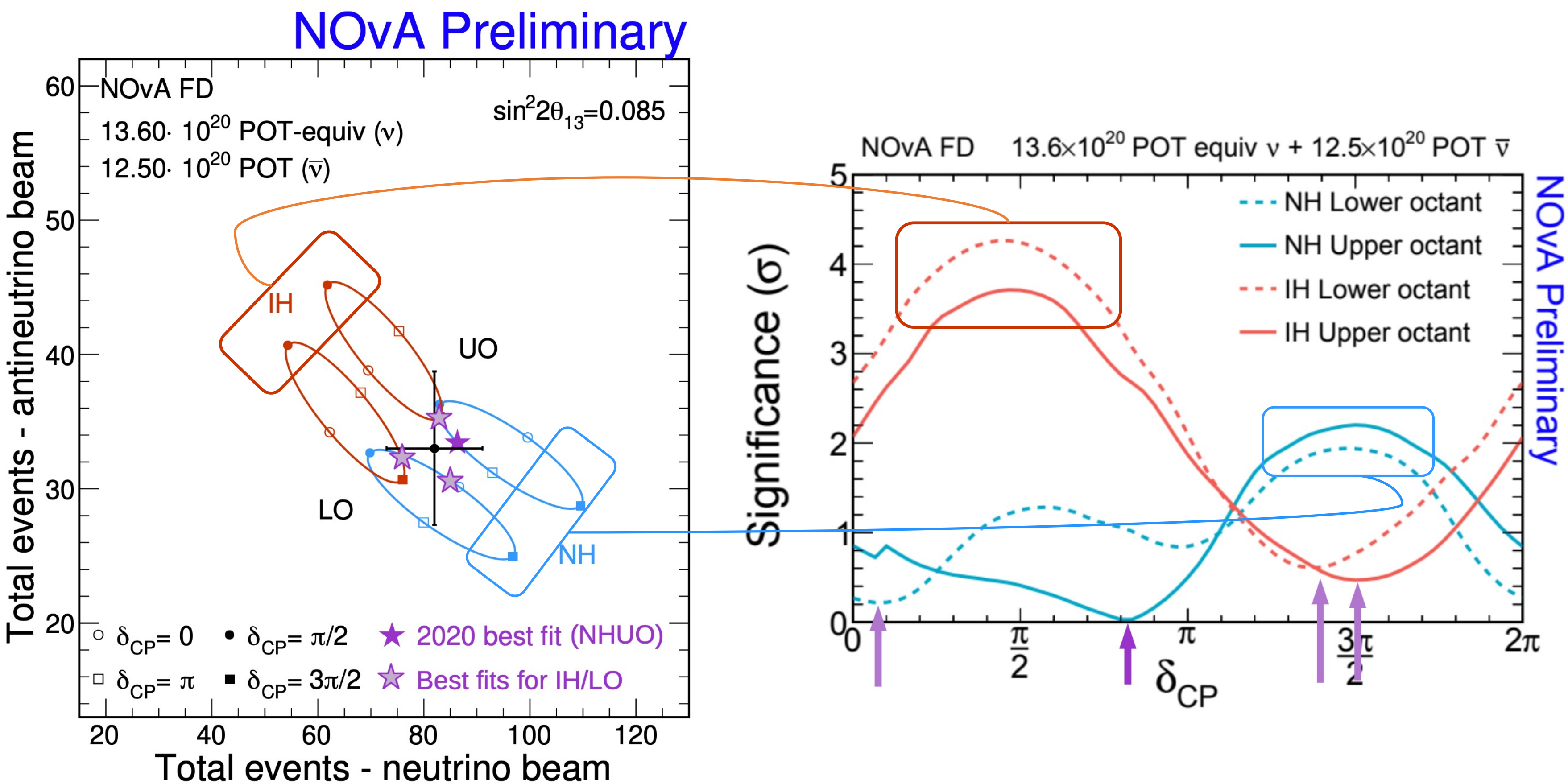




- Excludes {IH, $\delta_{CP} = \pi/2$ at > 3σ} &
  {NH, $\delta_{CP} = 3\pi/2$ at ~2σ}

- **Normal Hierarchy is preferred at 1.0σ**

Extracting Oscillation Parameters



➢ **NOvA data disfavors strong asymmetry in rates of ν_e and $\overline{\nu}_e$ appearance.**

GENIE

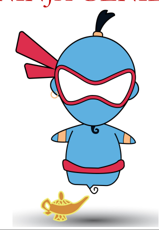
Neutrino Interactions : GENIE

- Using the latest GENIE v3.0.6
- Built a Custom-Model-Configuration (CMC) from the available collections of model
- 'Theory-driven' models with tune to external free-nucleon data were chosen as NOvA's nominal interaction model

GENIE N1810j_0211a *

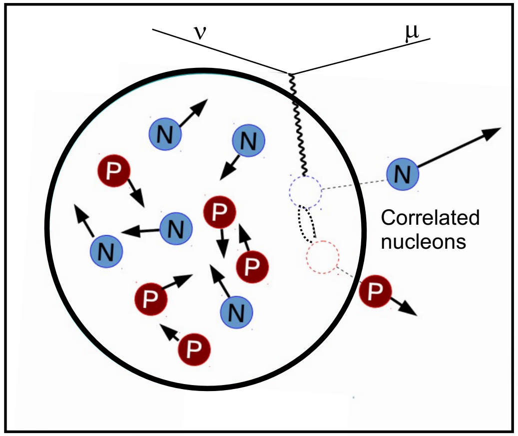
QE	MEC/2p2h	RES	DIS	FSI
• Valencia 1p1h • Z-expansion axial form factor	• Valencia MEC	• Berger-Sehgal	• Bodek-Yang	• hN Semi Classical Cascade

NINJA GENIE



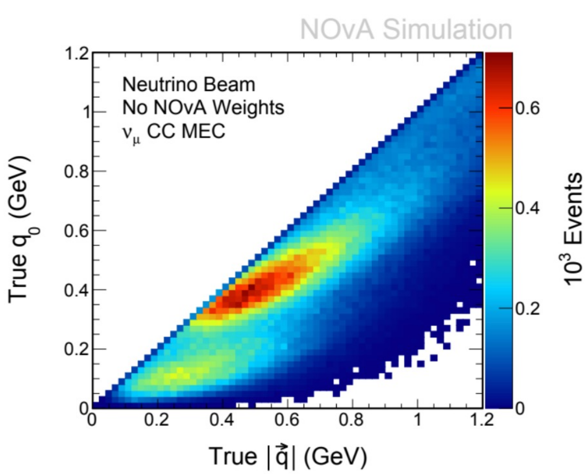
*We call our "tune" N1810j_0211a. It is built by starting with G1810b_0211a and substituting the Z-expansion QE axial form factor for the dipole one. This combination was not available in the 3.0.6 release, but it may be available in future versions

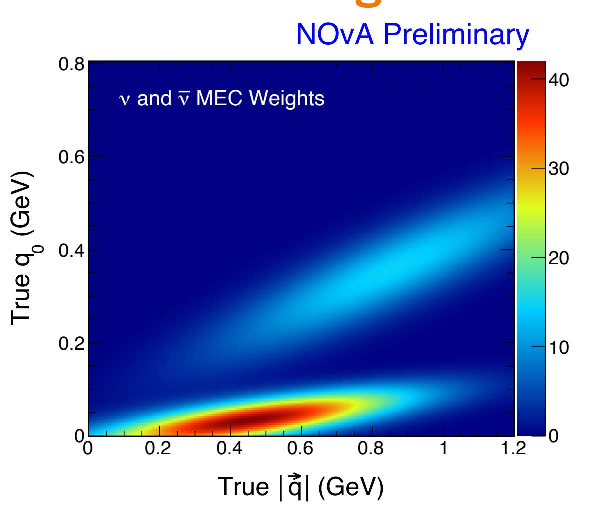
2p2h Tune

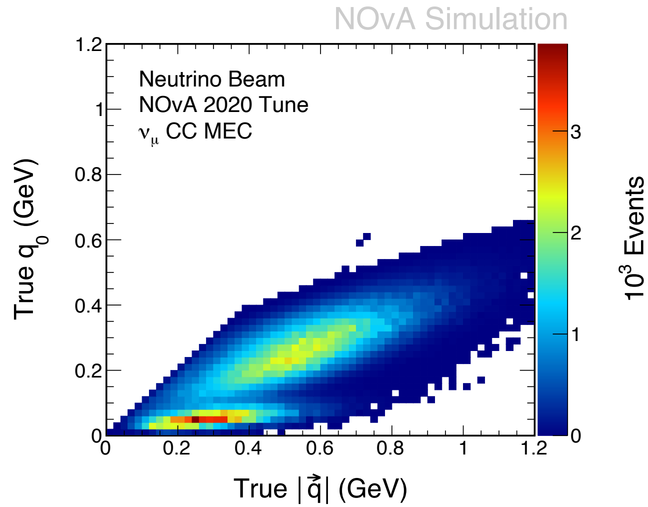


- "2p2h" or MEC (meson exchange current) interaction occurs when a neutrino interacts with a correlated pair of nucleons.
- NOvA tunes the MEC component of interaction simulation by doing a double gaussian fit to its data.

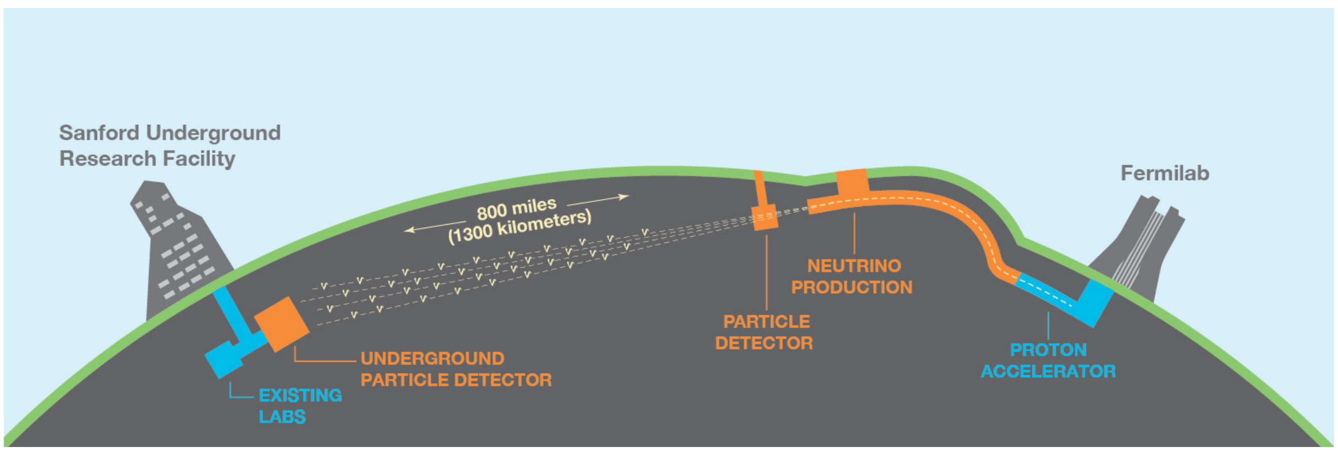
Valencia 2p2h x **MEC Weights** = **NOvA Tune**







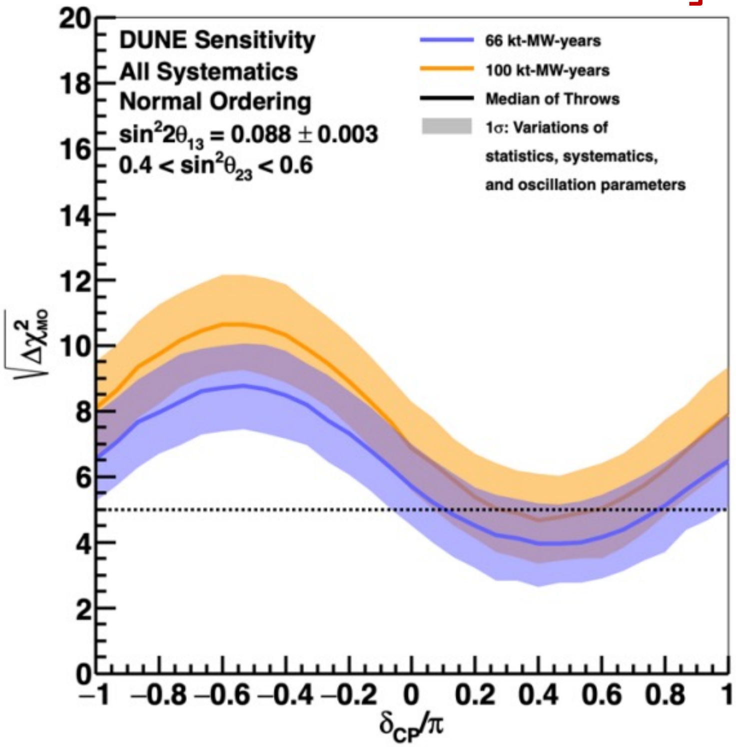
DEEP UNDERGROUND
NEUTRINO EXPERIMENT



DUNE Oscillation Sensitivities : Mass Ordering

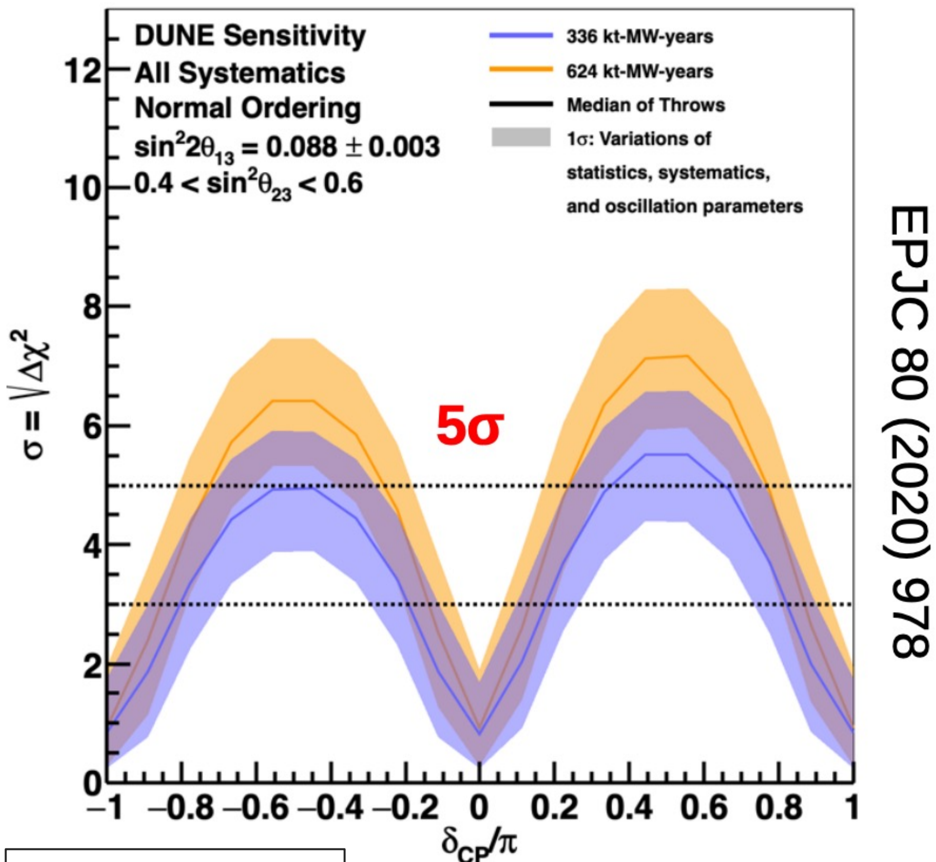
- DUNE is the flagship neutrino oscillation experiment scheduled to start taking physics data towards the end of this decade.
- The beam will start the run at 1.2MW with a planned upgrade to 2.4MW.
- The FD will consist of 4 x 17kt LAr modules.
- The sensitivities are quoted in kt-MW-year exposures rather than yearly timeline to avoid dependence on module construction and beam schedules.

Normal Ordering

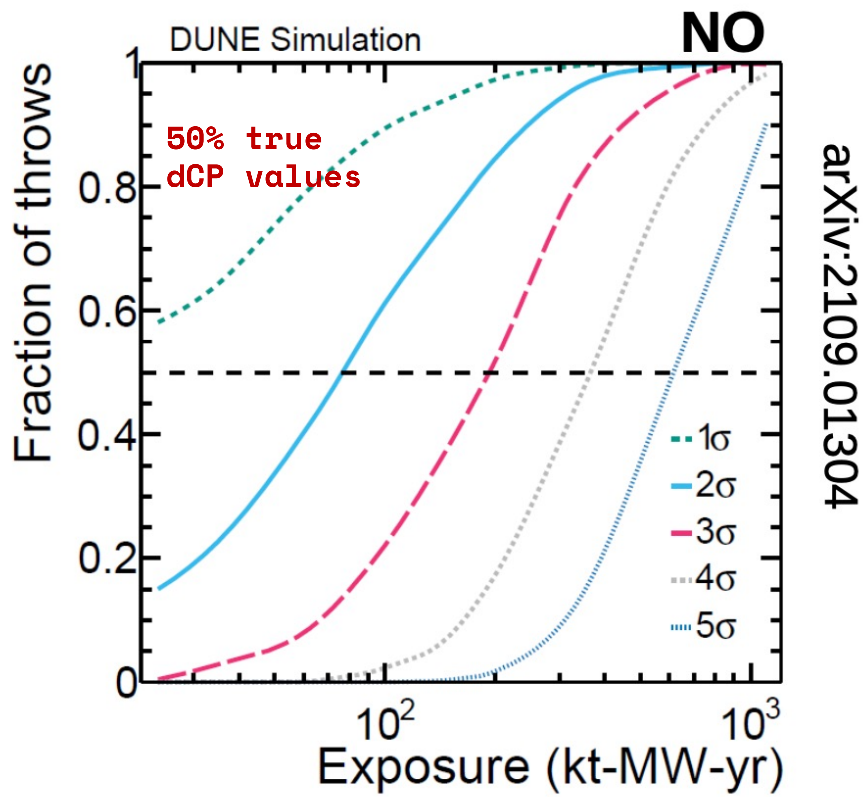


$$\Delta\chi^2_{MO} = \chi^2_{IO} - \chi^2_{NO}$$

DUNE Oscillation Sensitivities : CP Violation



$$\Delta\chi^2 = \chi^2_{0,\pi} - \chi^2_{\rm CPV}$$



- ➢ **DUNE has a median sensitivity for measuring 50% true dCP values above 3σ (5σ) after 197 (646) kt-MW-yr.**