

# Joint neutrino oscillation analysis from the T2K and NOvA experiments



**NO1 seminar, 17 February 2026**  
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## Joint neutrino oscillation analysis from the T2K and NOvA experiments

[The NOvA Collaboration](#) & [The T2K Collaboration](#)

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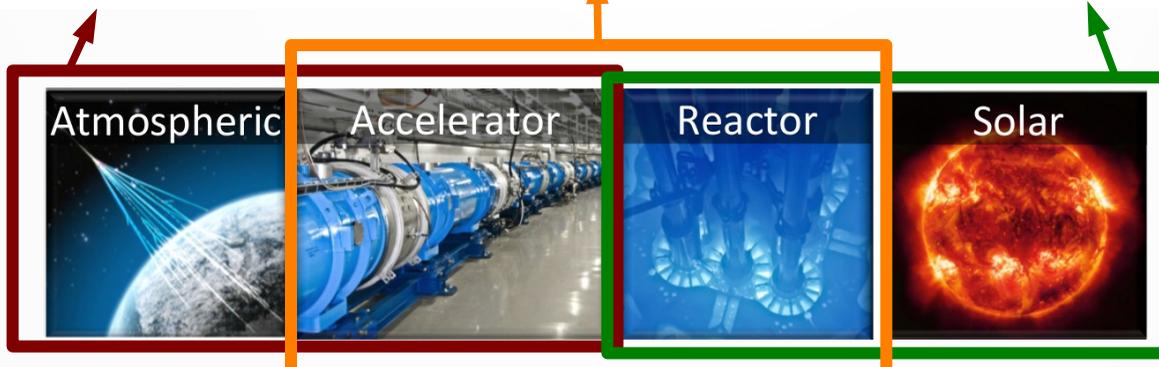
# Outline

- **Introduction: flavor-mass mixing, neutrino oscillations**
- Comparison of T2K and NOvA experiments
- Quest for CP violation in the neutrino sector
- Joint oscillation analysis
- Summary

# Flavor-mass mixing

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{\frac{i\alpha_1}{2}} & 0 & 0 \\ 0 & e^{\frac{i\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

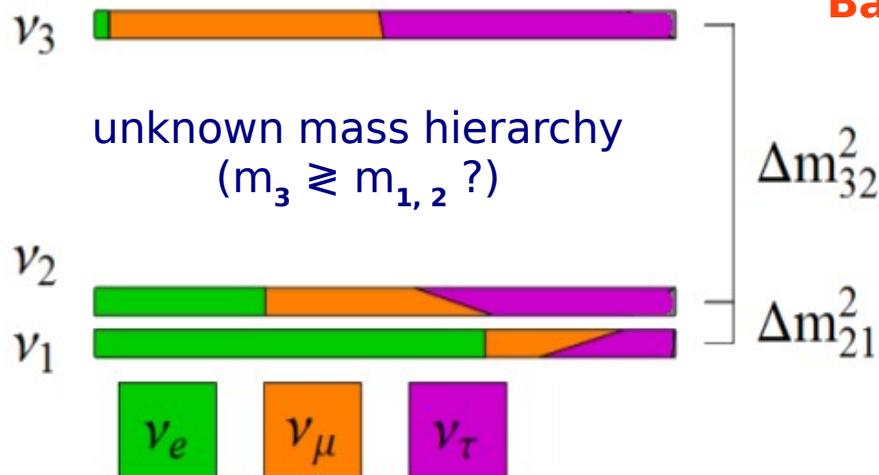
**Super-K, K2K,  
MINOS,  
OPERA  
NOvA, T2K**



Flavor-mass mixing described with PMNS matrix

**Super-K, SNO,  
KamLAND**

**DChooz, RENO, Daya  
Bay, MINOS, NOvA, T2K**



$c_{ij}, s_{ij} - \cos\theta_{ij}, \sin\theta_{ij}$  ( $\theta_{ij}$  - mixing angles),  
 $\delta_{CP}$  - CP violation (CPV) phase  
 $\alpha_1, \alpha_2$  - Majorana phases  
 (not relevant for neutrino oscillations)

**T2K and NOvA are sensitive to  
 $\Delta m^2_{32}, \theta_{23}, \theta_{13}$  and  $\delta_{CP}$ .**

# Oscillation probability in vacuum

Probability that a neutrino produced in  $\nu_\alpha$  flavour state will interact as neutrino in  $\nu_\beta$  state:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\delta_{\alpha\beta}}_{\text{Kronecker delta}} - 4 \sum_{i>j} \underbrace{\text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*)}_{\text{Elements of PMNS matrix}} \sin^2 \left( \underbrace{\Delta m_{ij}^2}_{\text{Difference of squared masses}} \underbrace{\frac{L}{4E}}_{\text{L - neutrino propagation distance, E - neutrino energy}} \right) \\ \pm 2 \sum_{i>j} \underbrace{\text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*)}_{\text{Elements of PMNS matrix}} \sin \left( \underbrace{\Delta m_{ij}^2}_{\text{Difference of squared masses}} \underbrace{\frac{L}{2E}}_{\text{L - neutrino propagation distance, E - neutrino energy}} \right),$$

Difference of squared masses  $\Delta m_{ij}^2 = m_i^2 - m_j^2$

L - neutrino propagation distance, E - neutrino energy

# CP violation

- CP symmetry – combination of charge (C) and parity (P) symmetry.
- Violation of CP implies that there is a difference between particles and antiparticles.
- CP violation is one of Sakharov's conditions for an explanation of the observed imbalance of matter and antimatter abundance in the Universe.
  - Discovered in quark sector.
- In neutrino sector it may be manifested in different oscillation probabilities (for neutrinos and antineutrinos).

# Three flavor $\nu_\mu \rightarrow \nu_e$ appearance probability

$$P(\nu_\mu \rightarrow \nu_e) \approx 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \left( 1 + \frac{2a}{\Delta m_{31}^2} (1 - 2s_{13}^2) \right)$$

Leading including matter effect

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta_{\text{CP}} - s_{12} s_{13} s_{23}) \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

CP conserving

$$- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta_{\text{CP}} \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

CP violating

$$+ 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta_{\text{CP}}) \sin^2 \Delta_{21}$$

Solar

$$- 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E} \cos \Delta_{32} \sin \Delta_{31}$$

Matter effect

$$c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}$$

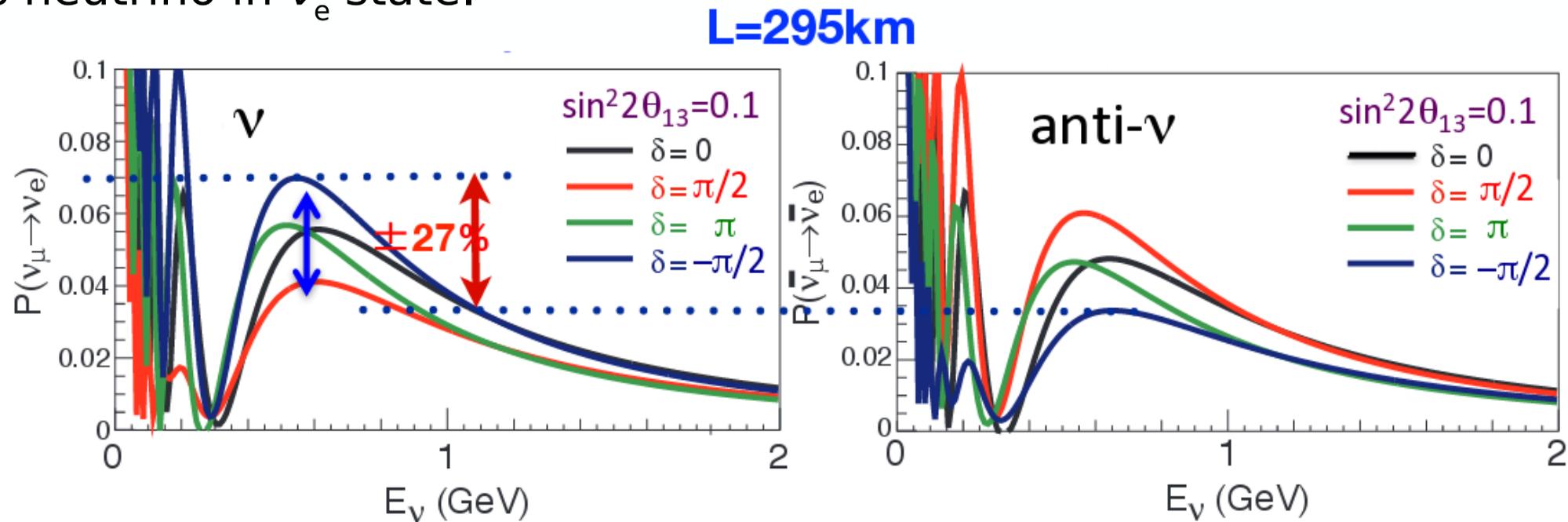
$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

$$a \equiv 2\sqrt{2}G_F n_e E = 7.56 \times 10^{-5} \text{eV}^2 \frac{\rho}{\text{gcm}^{-3}} \frac{E}{\text{GeV}}$$

replace  $\delta_{\text{CP}}$  by  $-\delta_{\text{CP}}$  and  $a$  by  $-a$  for  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

# Oscillation probability

Probability that a neutrino produced in  $\nu_\mu$  flavor state will interact as neutrino in  $\nu_e$  state.



Impact of  $\delta_{CP}$  violation phase for neutrinos and antineutrinos. Maximal CP violation results in approximately  $\pm 27\%$  change of the  $\nu_e$  appearance probability (wrt. CP conserving values).

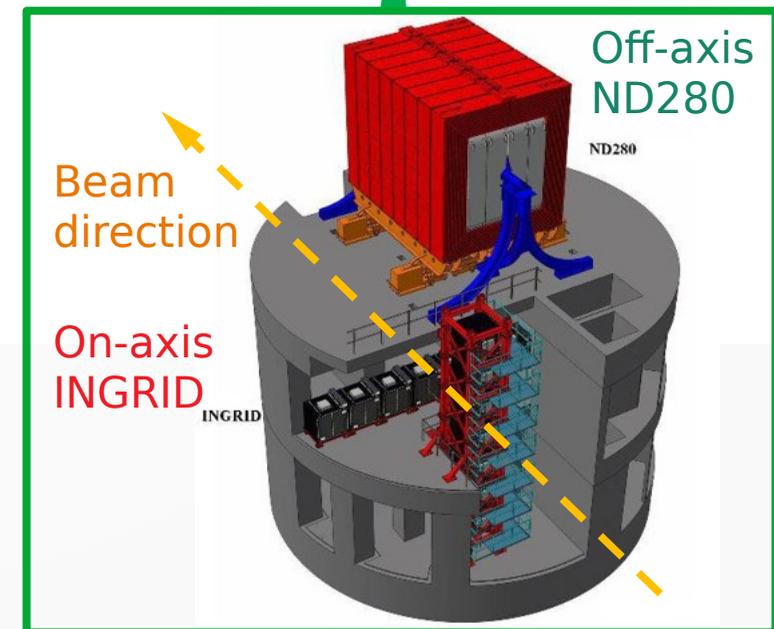
Matter effects small compared to CP violation (difference between  $\delta_{CP} = 0, \pi$ ).

# Outline

- Introduction: flavor-mass mixing, neutrino oscillations
- **Comparison of T2K and NOvA experiments**
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# T2K experiment

- T2K is a long-baseline neutrino experiment. Two near detectors (INGRID, ND280) are used to study beam properties ~280 m from the source in J-PARC.
- Super-Kamiokande is used as the far detector.
- Started taking data in 2010,  $\nu_e$  appearance discovered in 2013.
- Contribution of T2K group at IFJ PAN:
  - Cross-section analyses
  - Data taking and detector expert shifts
  - ND280 upgrade

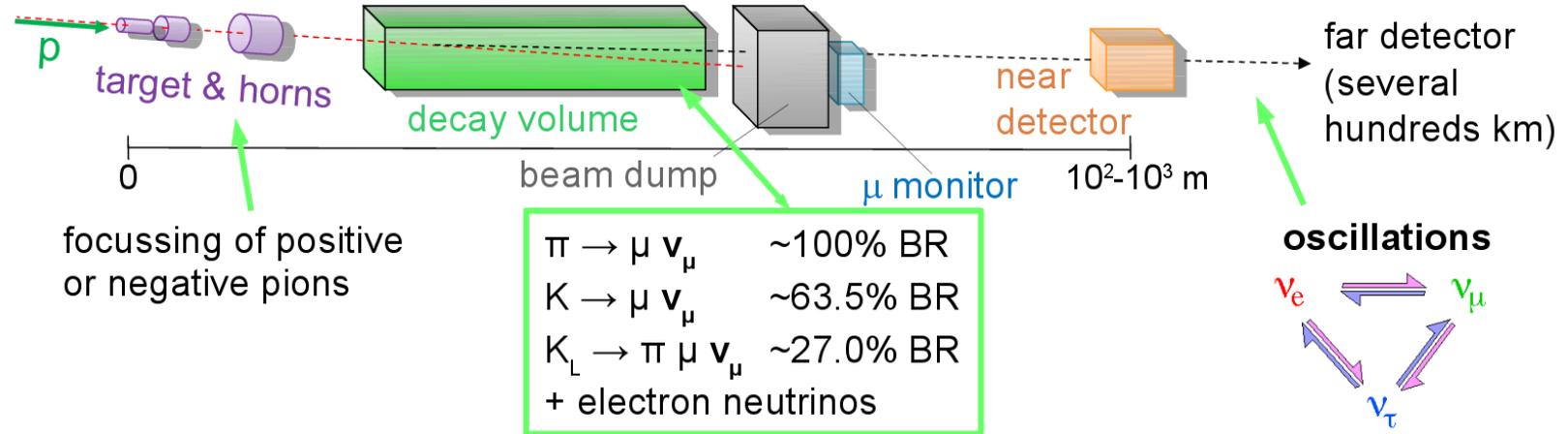


T2K

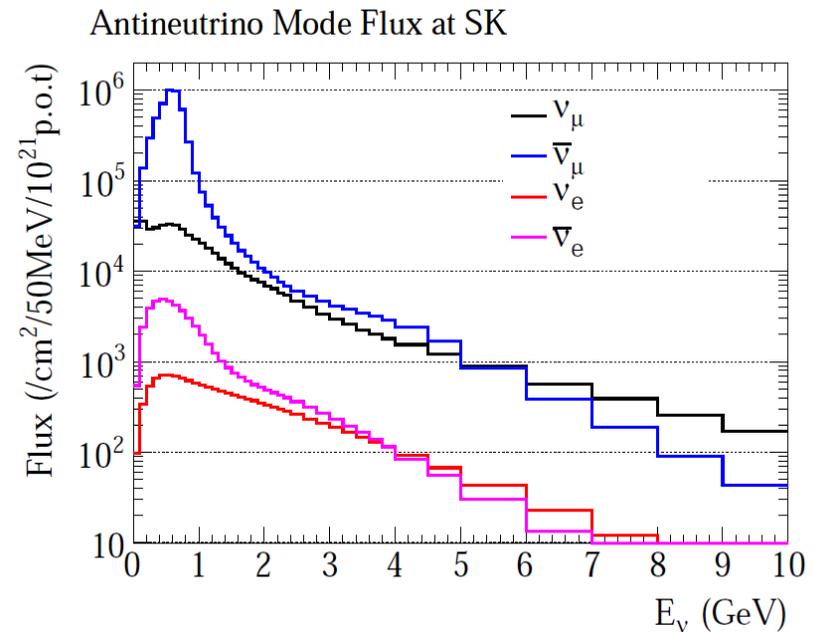
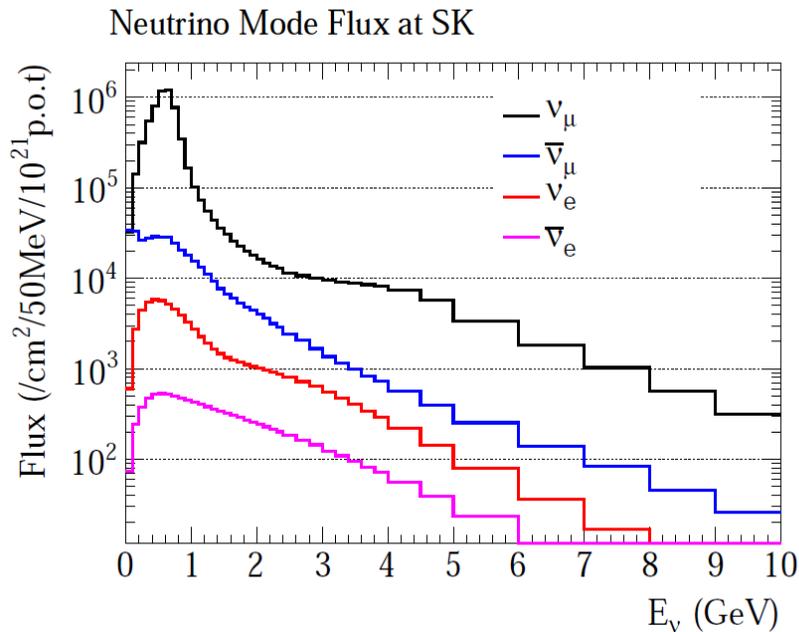
# T2K beam



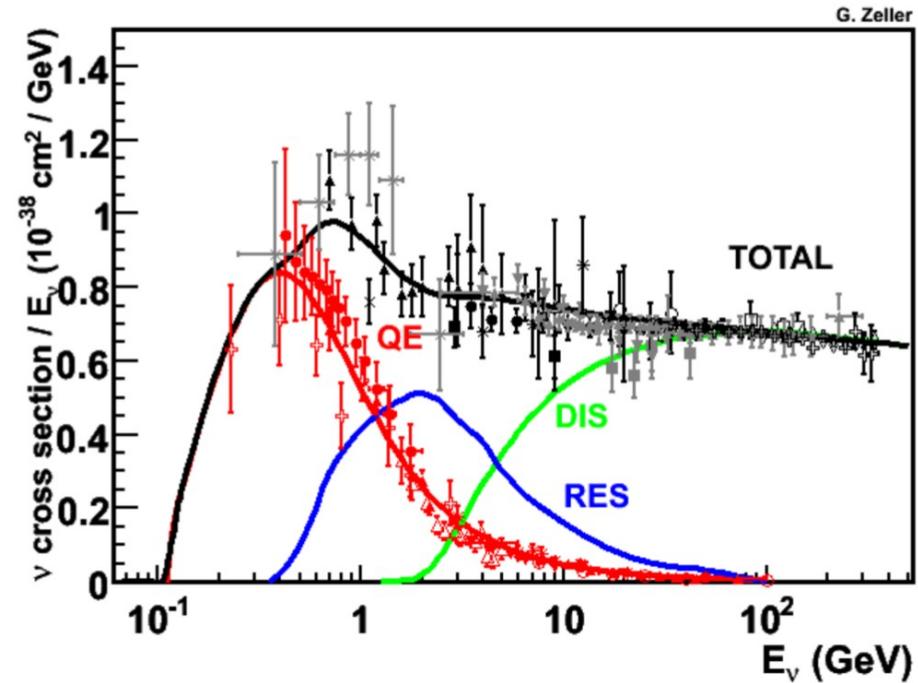
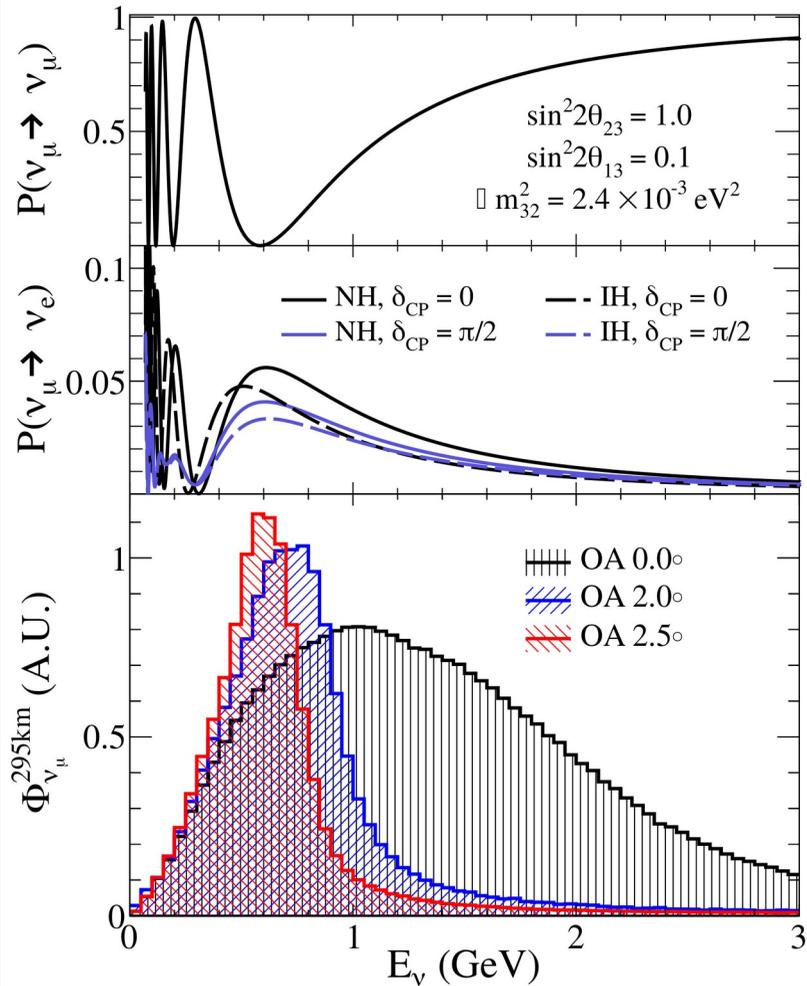
Flux predictions tuned for hadron production results from NA61/SHINE (measurements on T2K target replica)



Beam can operate in neutrino or antineutrino mode.

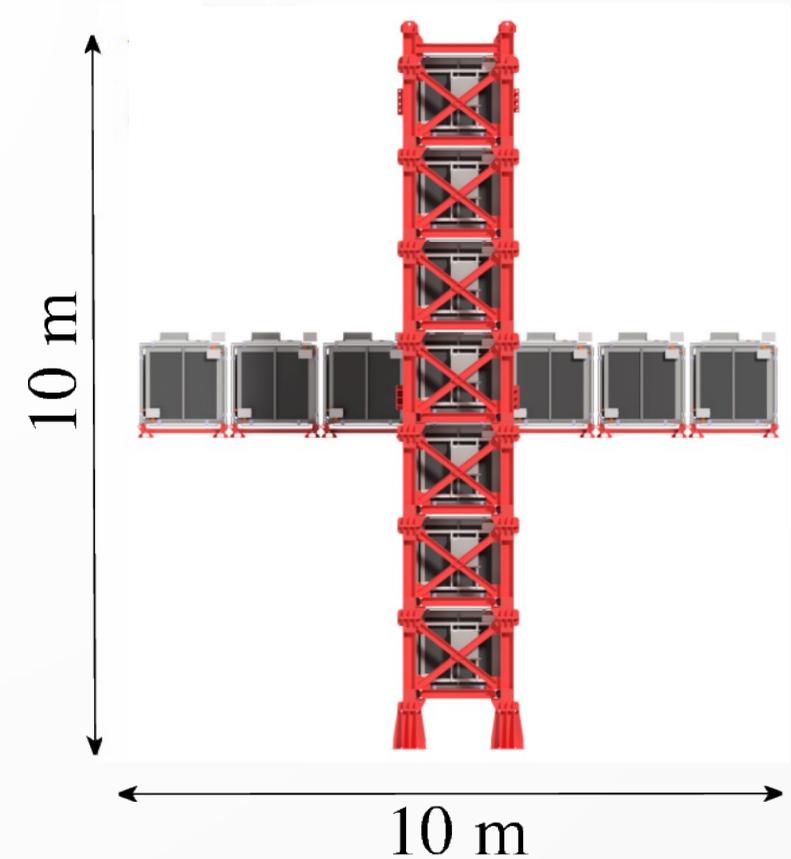
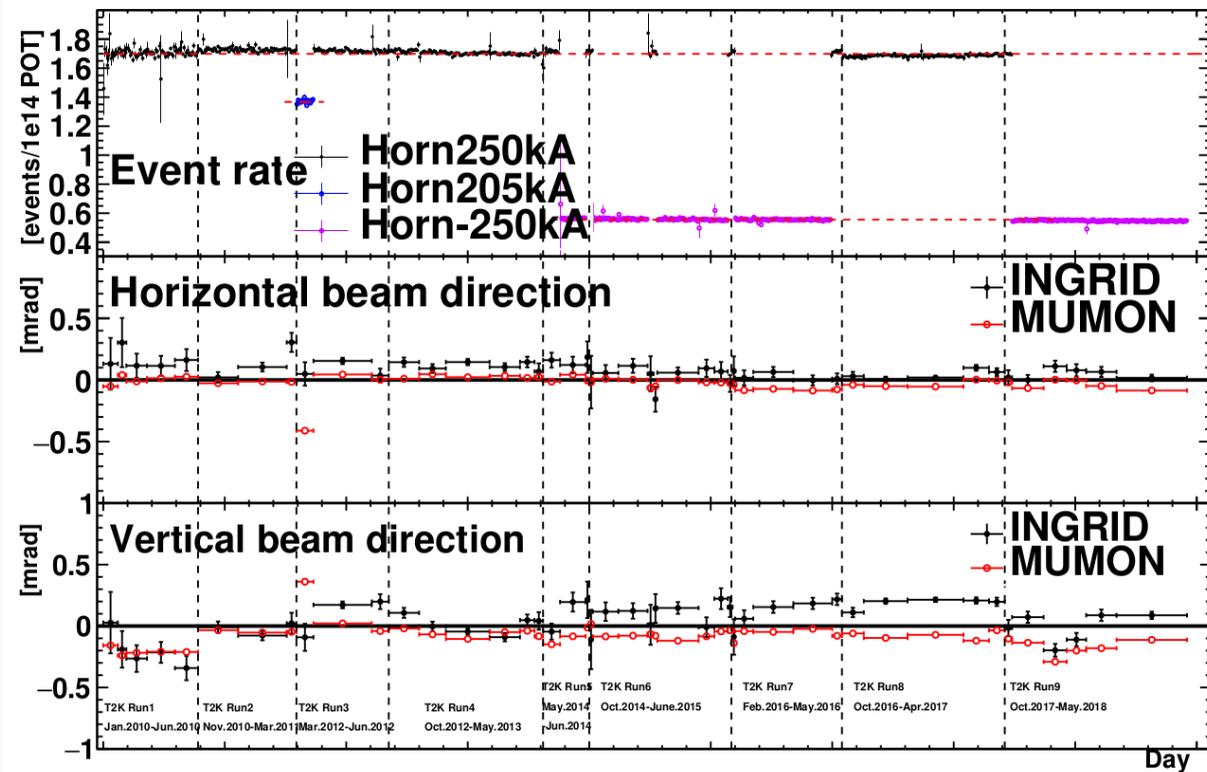


# Off-axis strategy



- Off-axis strategy enhances oscillation effect and contribution of CC quasielastic (CCQE) interactions.
- Around T2K beam peak ( $\sim 600$  MeV) mostly CCQE and resonant interactions occur.
- Shift in off-axis angle  $\delta\text{OA} \sim 1\text{mrad}$  ( $0.057^\circ$ )  $\rightarrow$  shift in energy peak  $\delta E/E \sim 2\%$  at far detector

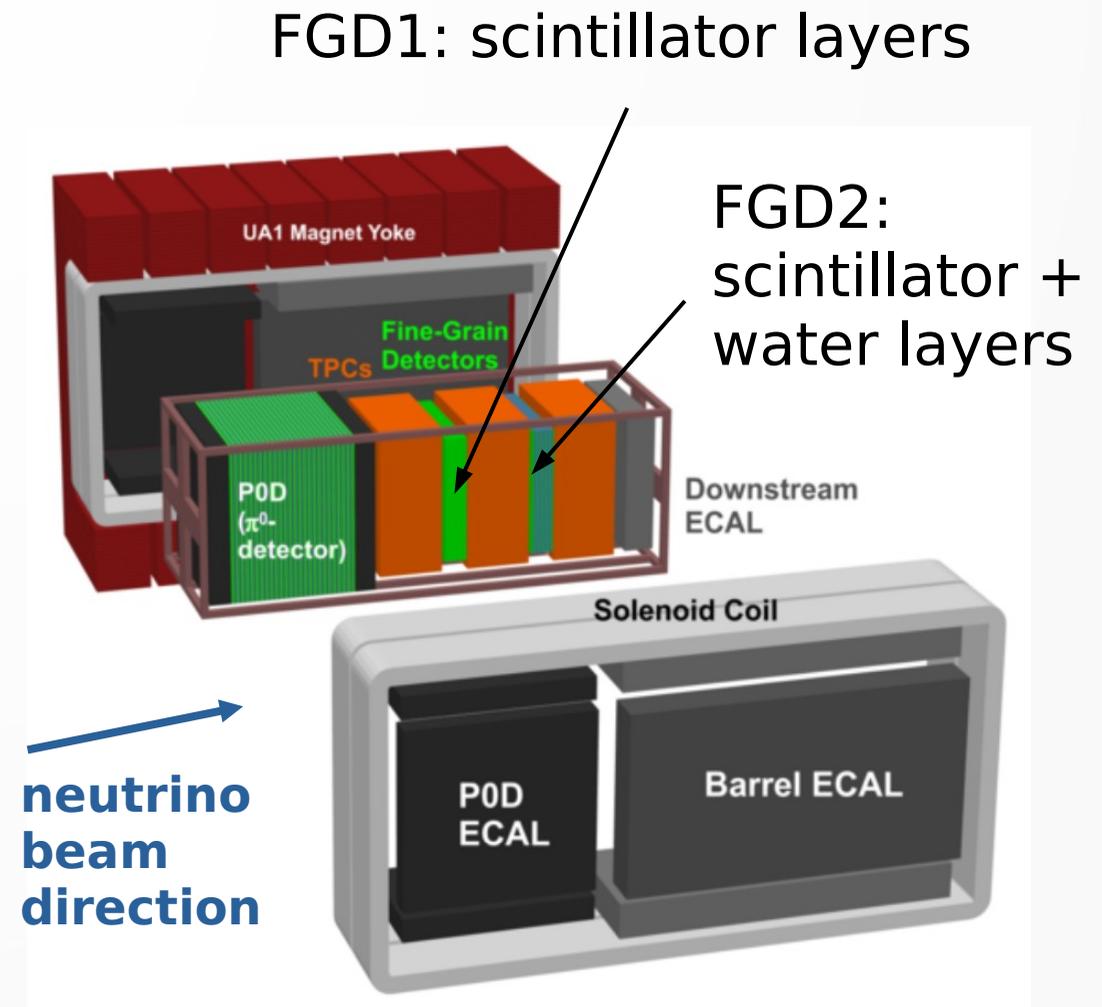
# On-axis near detector: INGRID



- Cross-shaped detector composed of 14 Fe/scintillator modules.
- Monitors beam's direction, profile and intensity.
- MUMON - muon monitor (for muons exiting decay volume)

# Off-axis near detector: ND280

- ND280 is a multipurpose detector used to constrain the off-axis flux and neutrino interaction models used in the oscillation analysis.
- CC interactions are studied in the tracker, made of two FGDs (fine grained detectors - scintillators) and three gaseous TPCs.
- FGDs serve as targets and provide good vertex and track resolution.
- Magnetic field allows for charge and momentum measurement.
- Energy loss in the TPCs allows for particle identification.

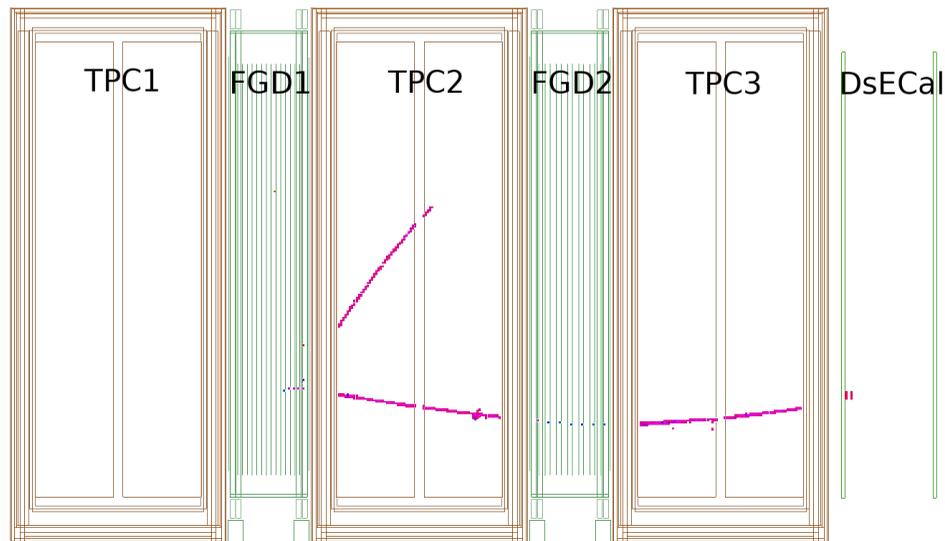


Exploded view of ND280  
Old design 2010-2022

# ND280 data samples

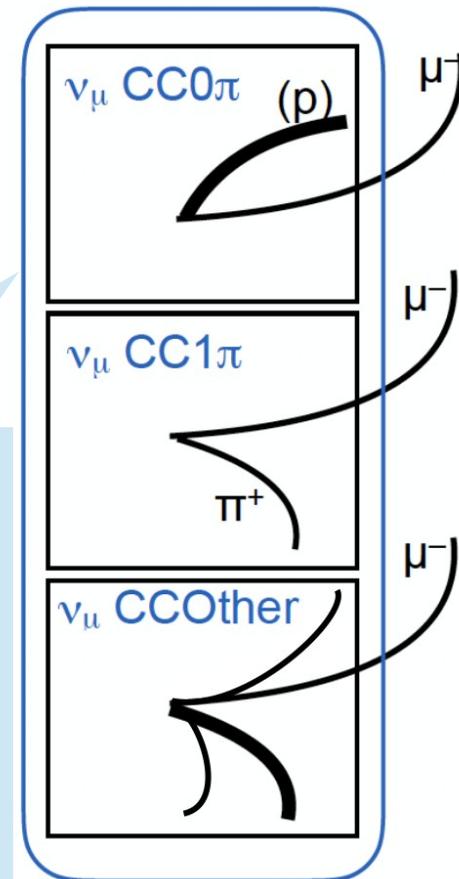
- Multiple ND280 samples used in the oscillation analysis:
  - For neutrino and antineutrino beam modes
  - Interaction in FGD1 or FGD2
  - Different signatures with respect to particles multiplicity

Event number : 135909 | Partition : 63 | Run number : 4200 | Spill : 0 | SubRun number : 31 | Time : Mon 2010-03-22 18:52:28 JST | Trigger: Beam Spill



ND280 event display (tracker region)

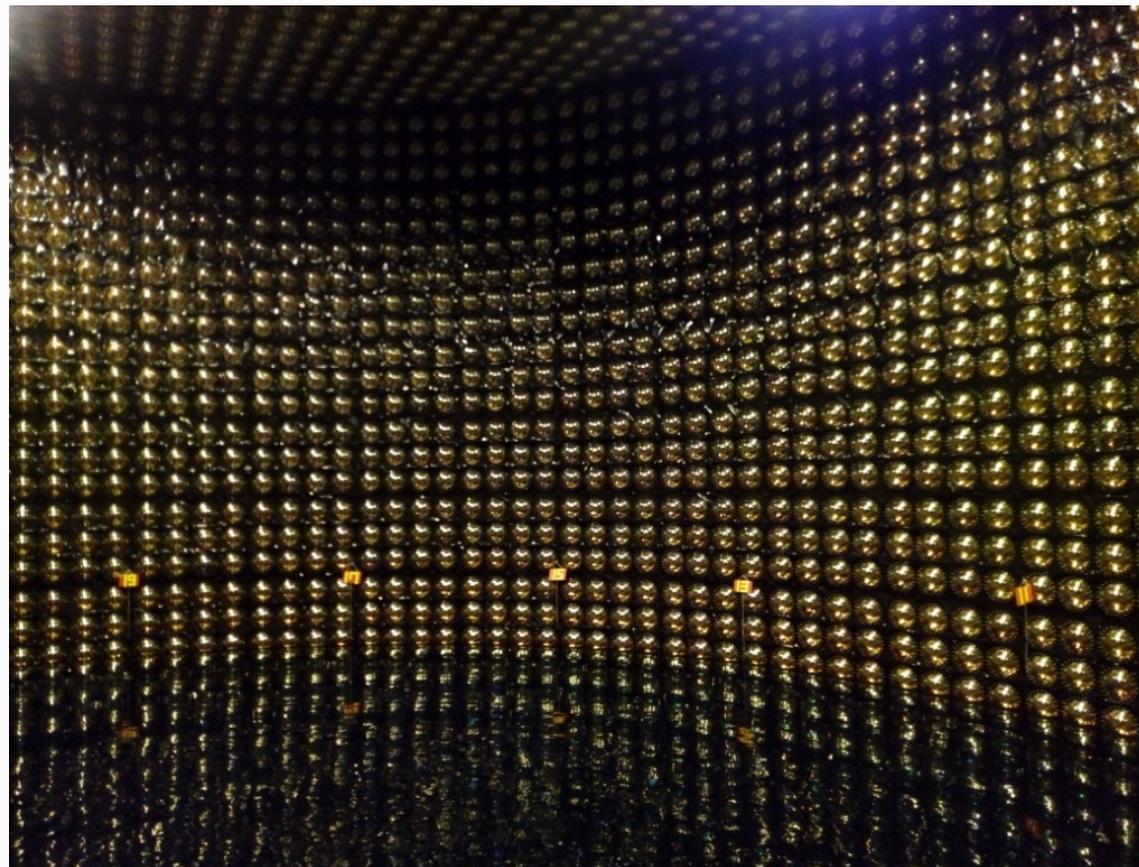
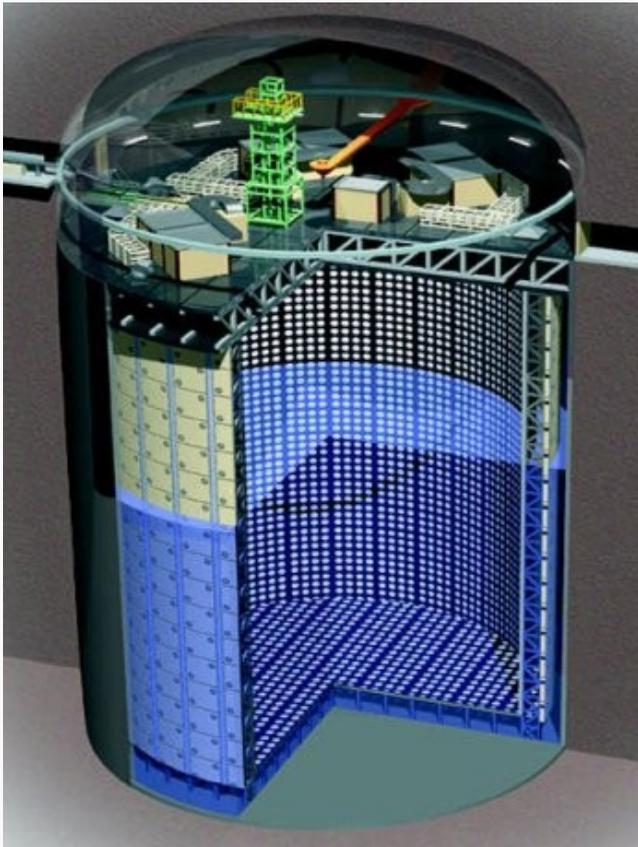
Three basic signatures used for classification. Divided into further subsamples for neutrino beam mode.



Upgraded ND280 samples not included in the oscillation analysis yet.

# Far detector: Super-Kamiokande

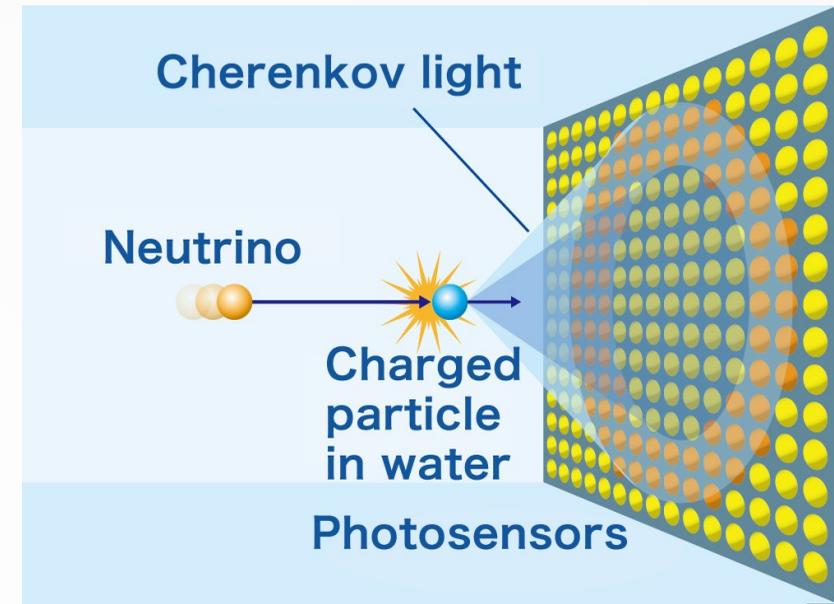
- 50 kton water Cherenkov detector
  - 39 m in diameter, 41 m in height
- Over 10000 PMTs measure the Cherenkov light inside the tank.



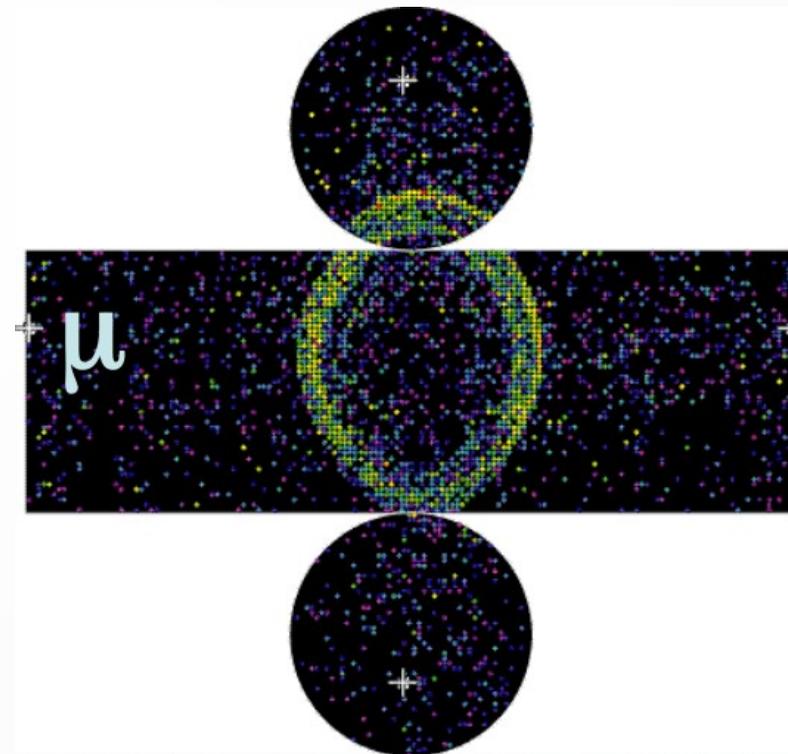
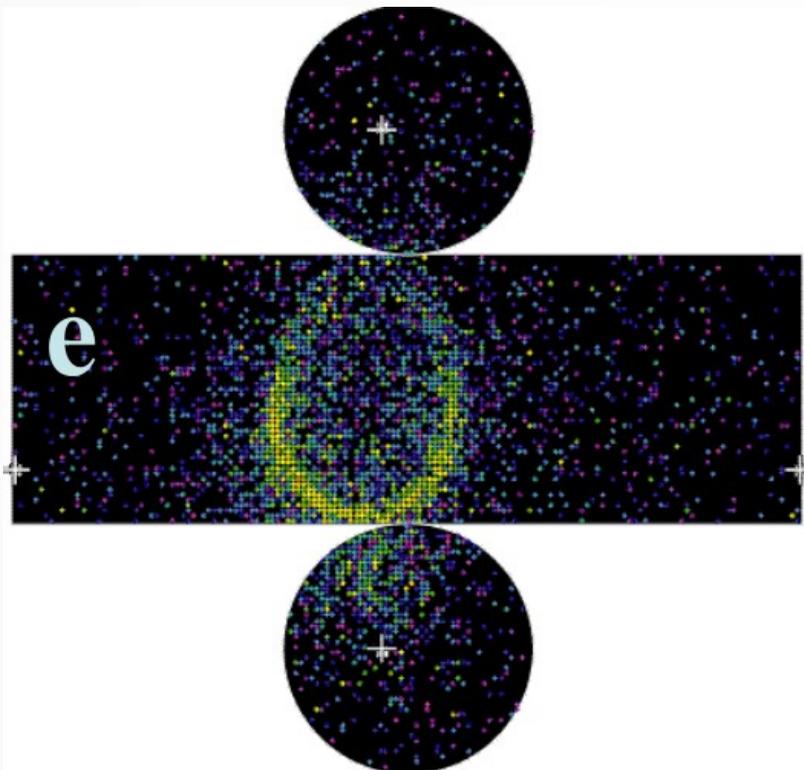
Tank refurbishment shift, July 2018



- Cherenkov radiation appears when charged particle propagates with velocity  $v > c/n$
- For T2K energy scale most nucleons are under Cherenkov threshold
- Single ring - signature of CCQE interaction

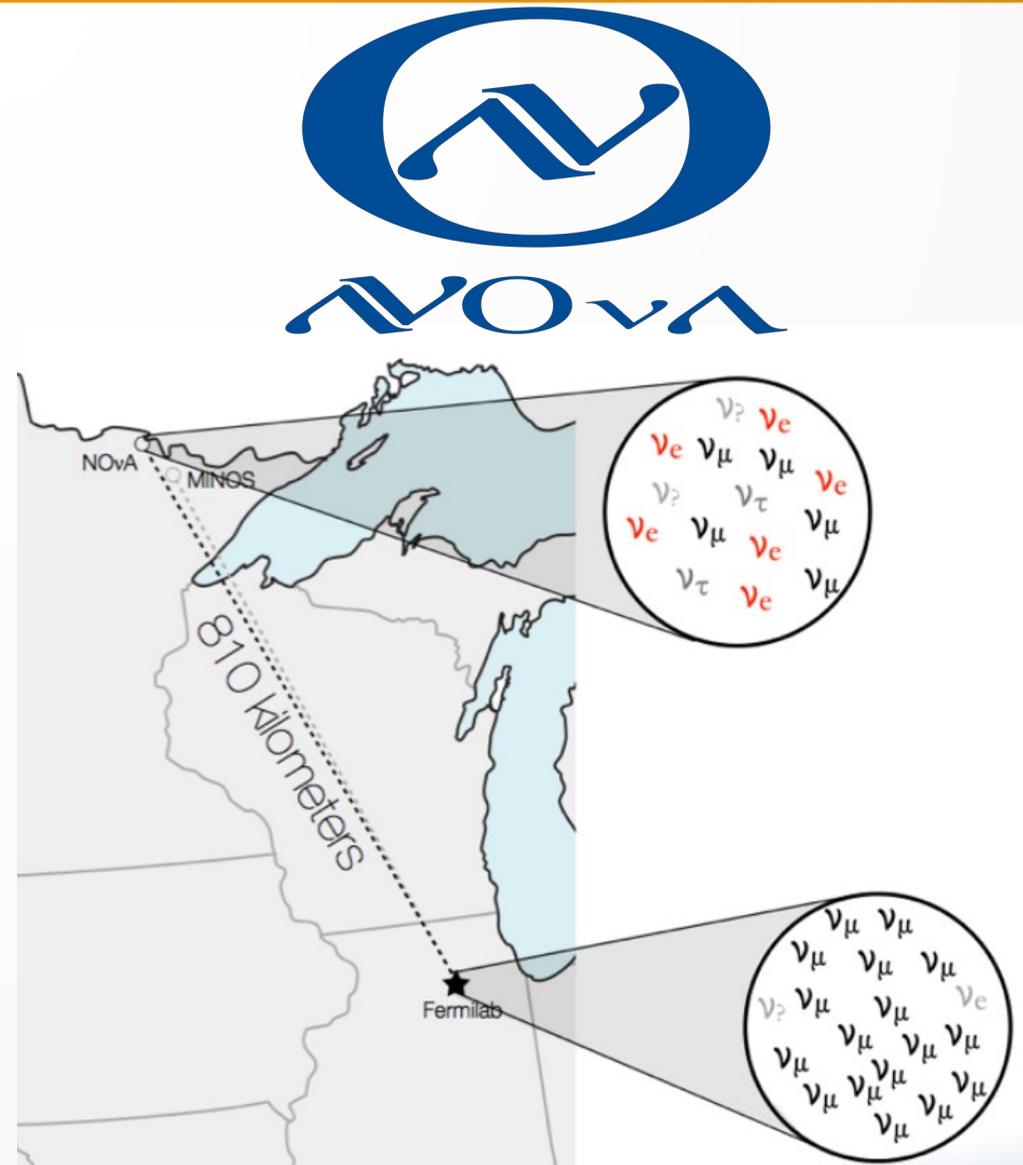


**Very good  $e/\mu$  separation in Super-K!  
~1% mis-id**



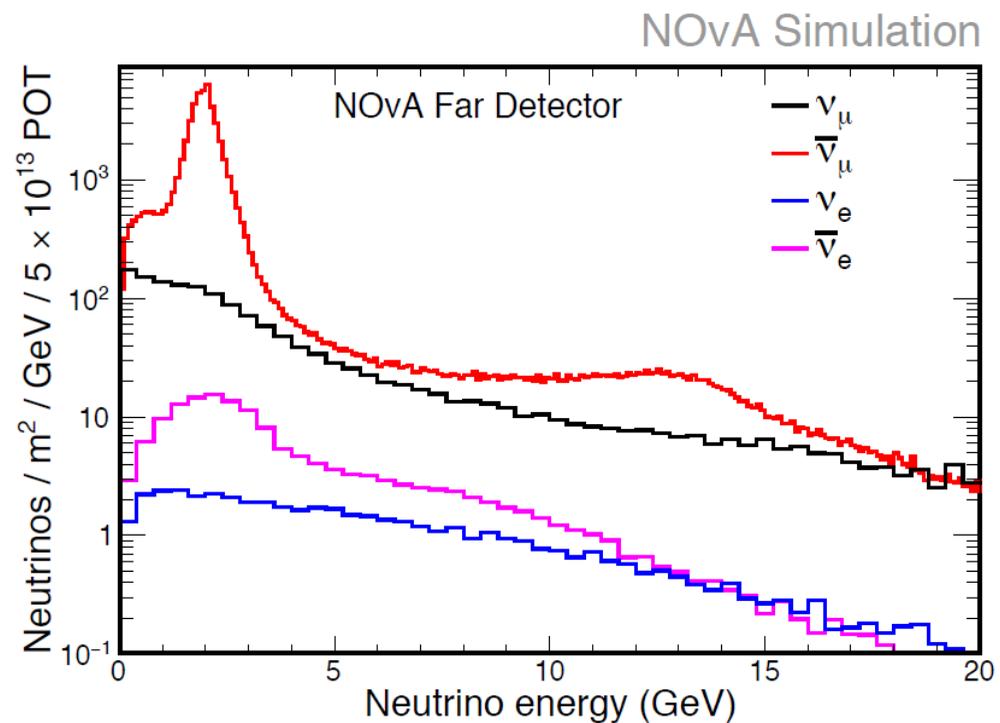
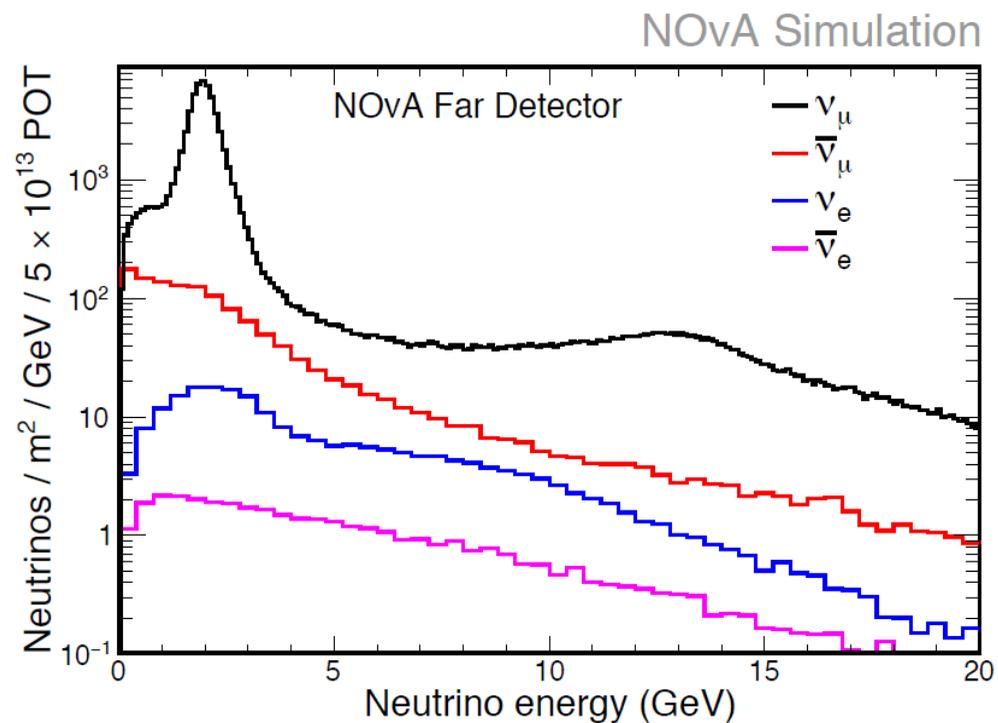
# NOvA experiment

- NOvA is a long-baseline neutrino oscillation experiment in the United States. It started taking data in 2014.
- Neutrino beam is produced at Fermilab.
- Near detector located 1 km downstream from the beam production target.
- Near and Far detector are functionally identical and situated 809 km apart, both 14 mrad off-axis.



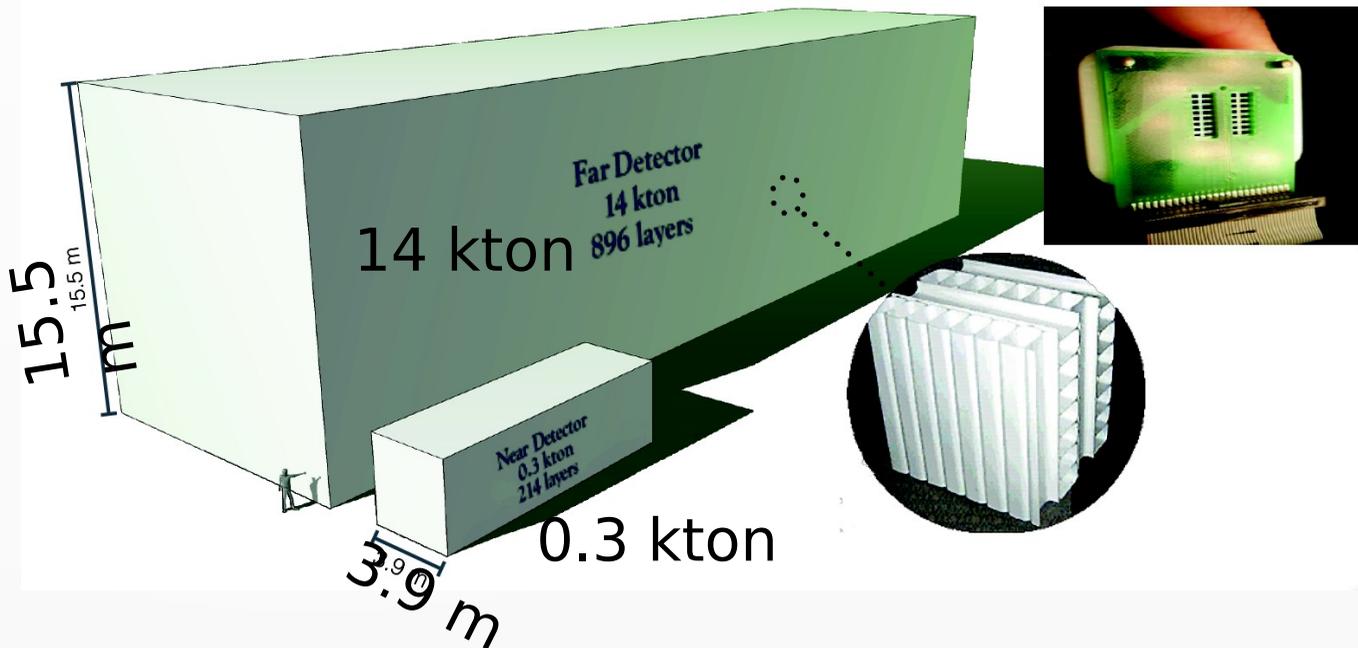
# NuMI beam

- Fermilab's Neutrinos at the Main Injector (NuMI) beam.
- Beam may be used in neutrino or antineutrino mode.
- Higher neutrino energies than in T2K beam.

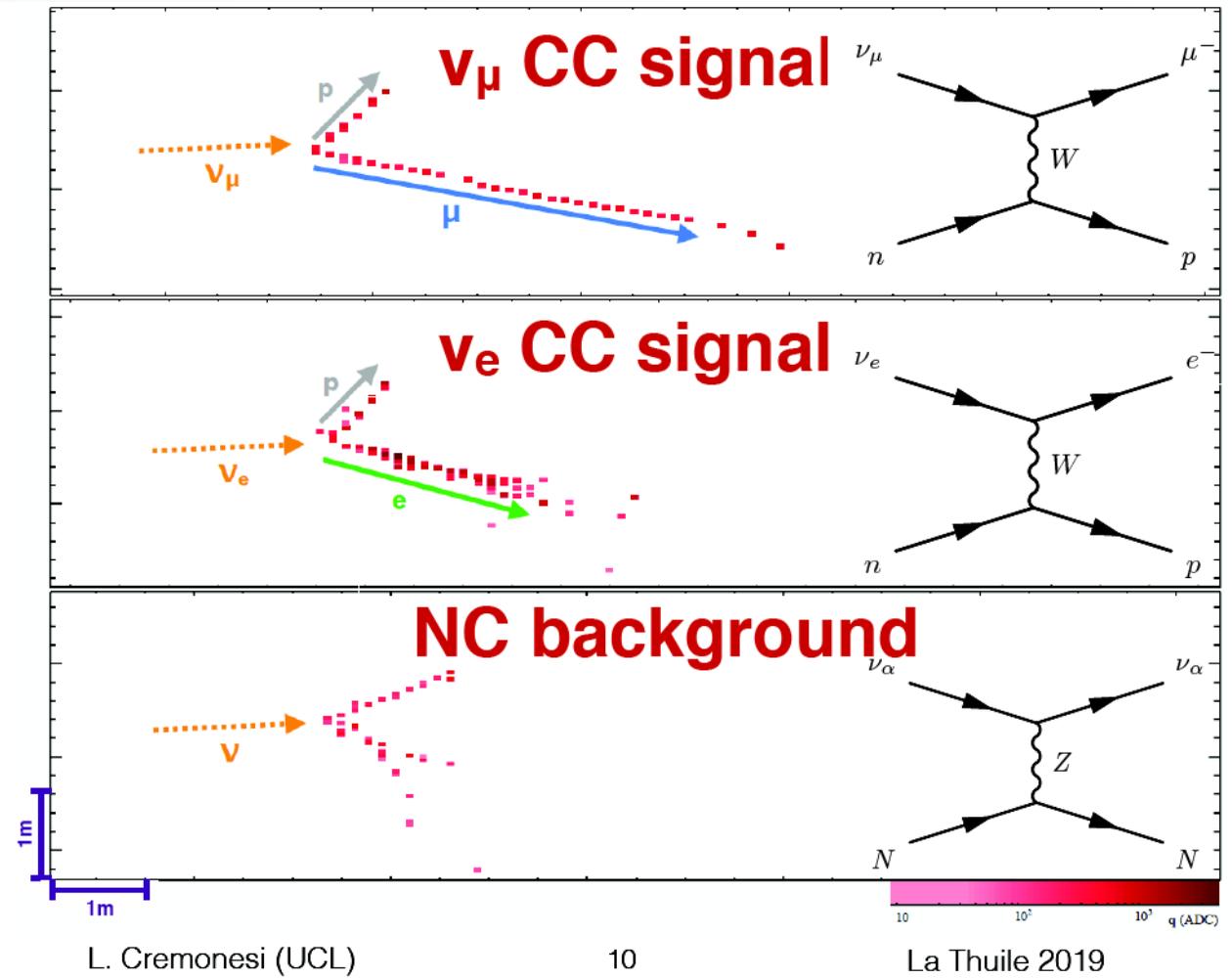


# NOvA detectors

- Both far and near detector are tracking calorimeters based on the same detection technique.
- Layers of plastic cells with alternating horizontal and vertical orientation with liquid scintillator inside.
- Very good muon and electron classification.



# NOvA event signatures



- The signature of a  $\nu_\mu$ -CC interaction is a long, straight muon track.
- A  $\nu_e$ -CC interaction is characterised by a shorter, wider shower.
- NC interaction results in a diffuse activity from the nuclear recoil.

# T2K-NOvA: Notable differences

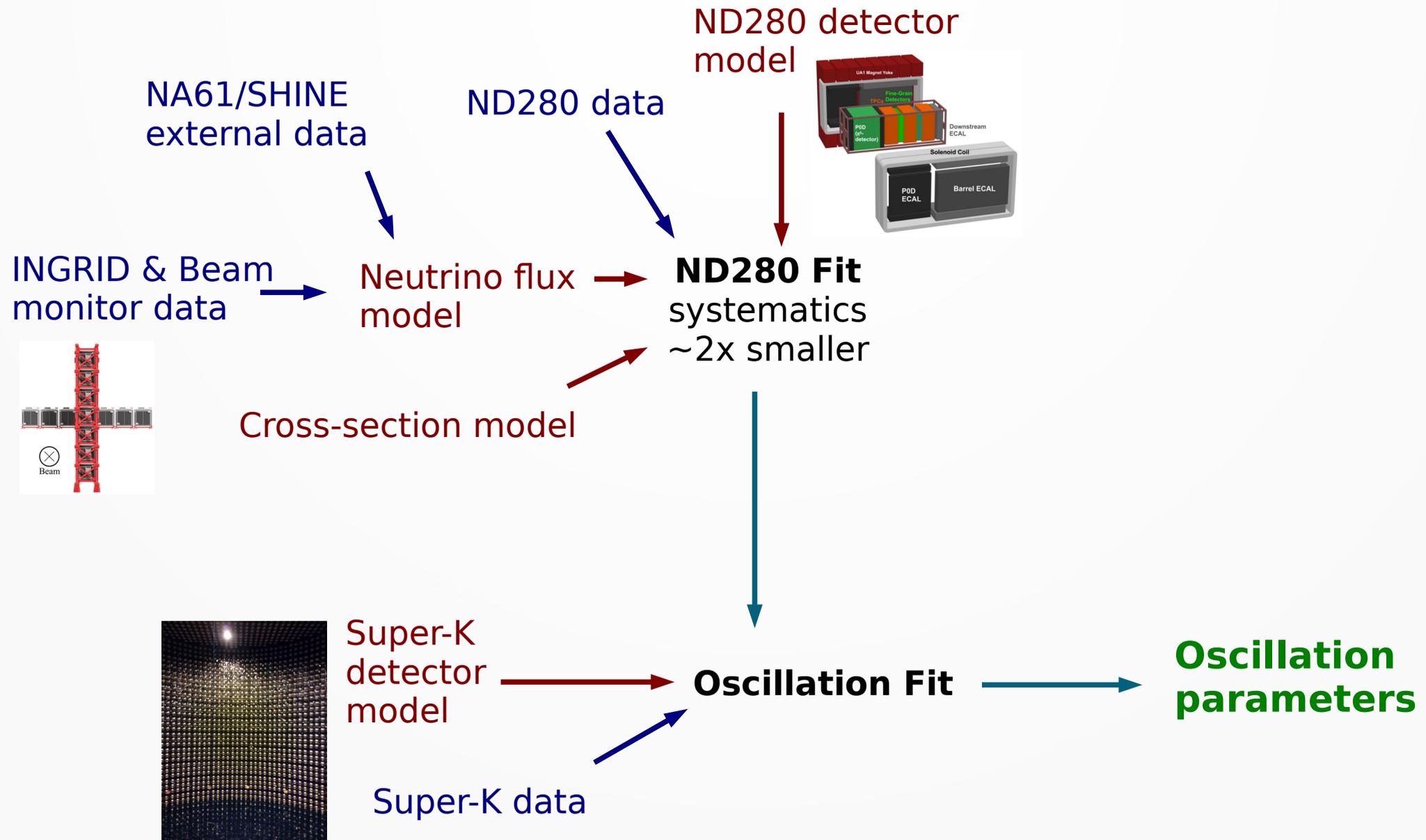
T2K	NOvA
Flux peaks at $\sim 0.6$ GeV	Flux peaks around 2.0 GeV
295 km baseline	810 km baseline
Different ND and FD technologies	Functionally identical ND and FD
CCQE dominant interaction mode	Broad mix of interaction modes
NEUT	GENIE
$E_{\text{rec}}$ from lepton kinematics	Calorimetric energy reconstruction
ND constrains model parameters	ND used for extrapolation technique

At higher energies and longer baseline NOvA is more sensitive to the matter effects.

Baryonic resonant interaction and deep inelastic scattering become more significant.

Kevin Wood,  
talk at T2K collaboration  
meeting 10.2020

# Oscillation analysis à la T2K



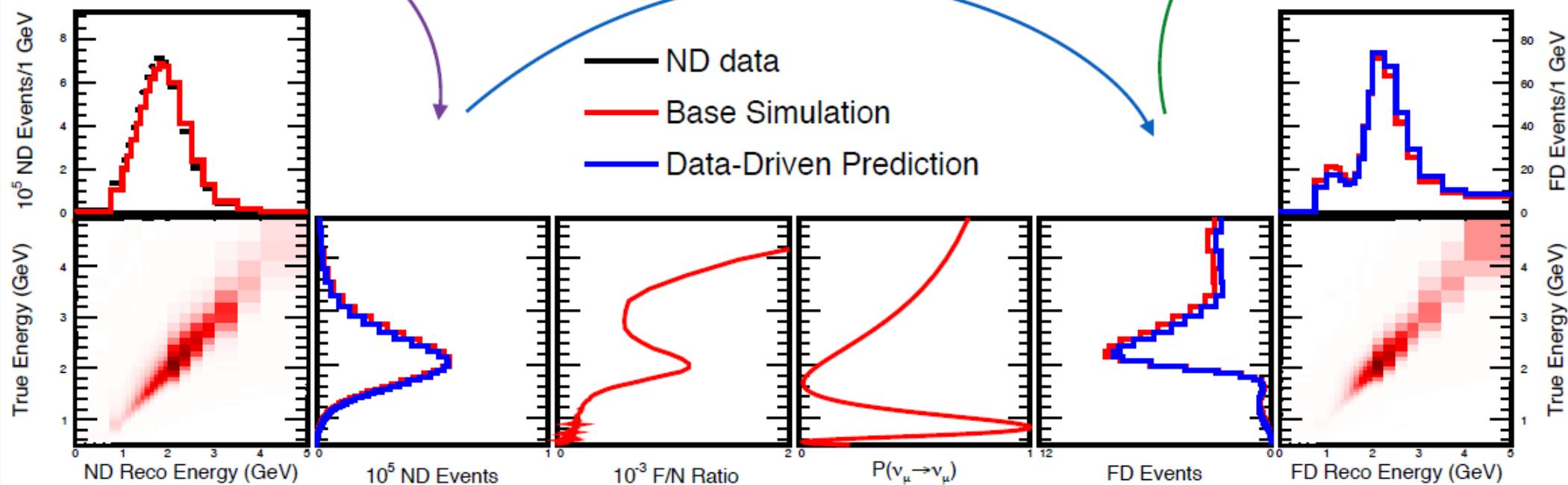
# Oscillation analysis à la NOvA

Translate ND data/  
MC observation to  
true energy

Oscillate  
ratio to the FD

Smear back into  
reconstructed  
energy

La Thuile 2019  
talk by Linda  
Cremonesi

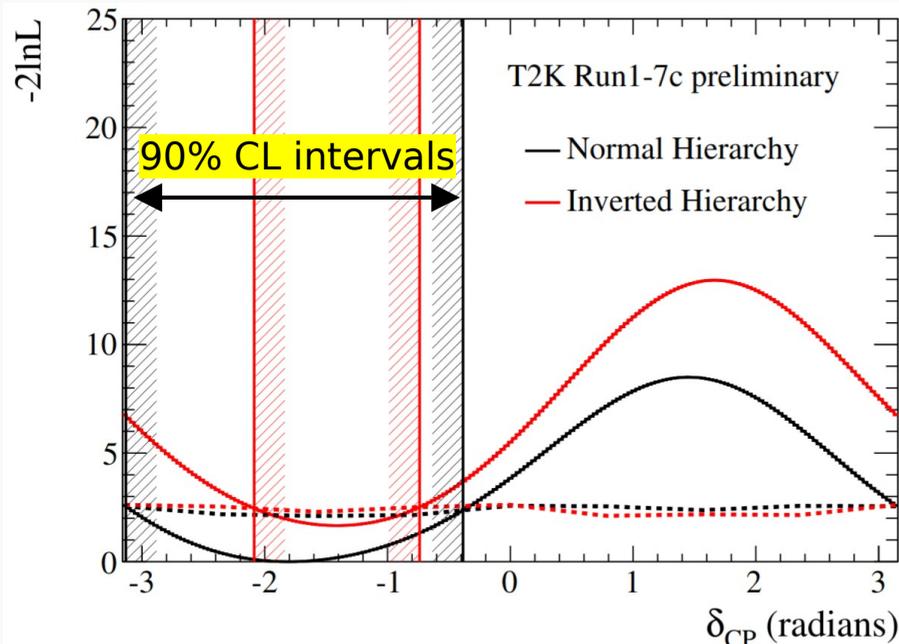


# Outline

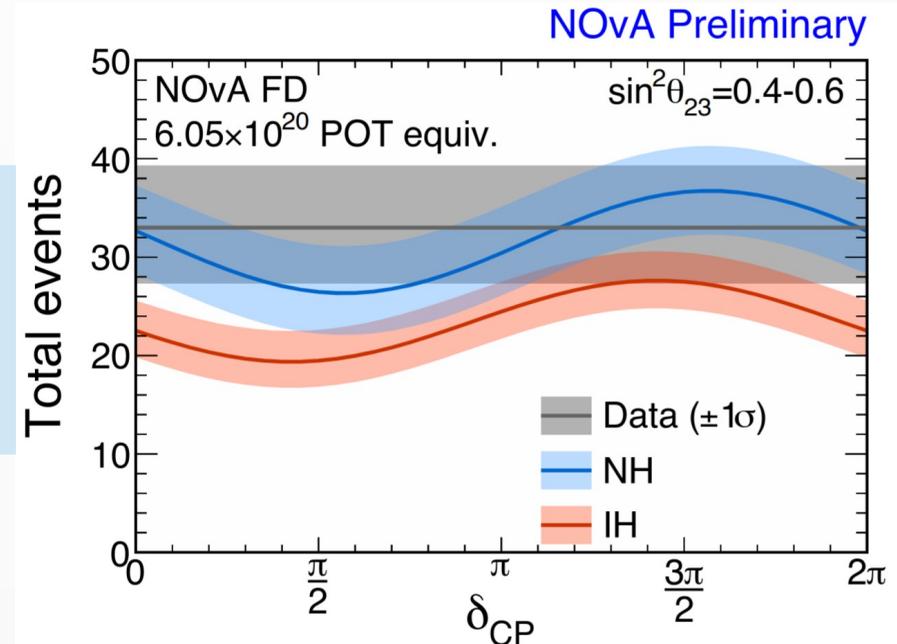
- Introduction: flavor-mass mixing, neutrino oscillations
- Comparison of T2K and NOvA experiments
- **Quest for CP violation in the neutrino sector**
- Joint oscillation analysis
- Summary

# CP violation search (history)

- Both T2K and NOvA measure neutrino oscillation parameters, including CP violation phase.
- For the past decade they kept publishing results of their independent analyses.

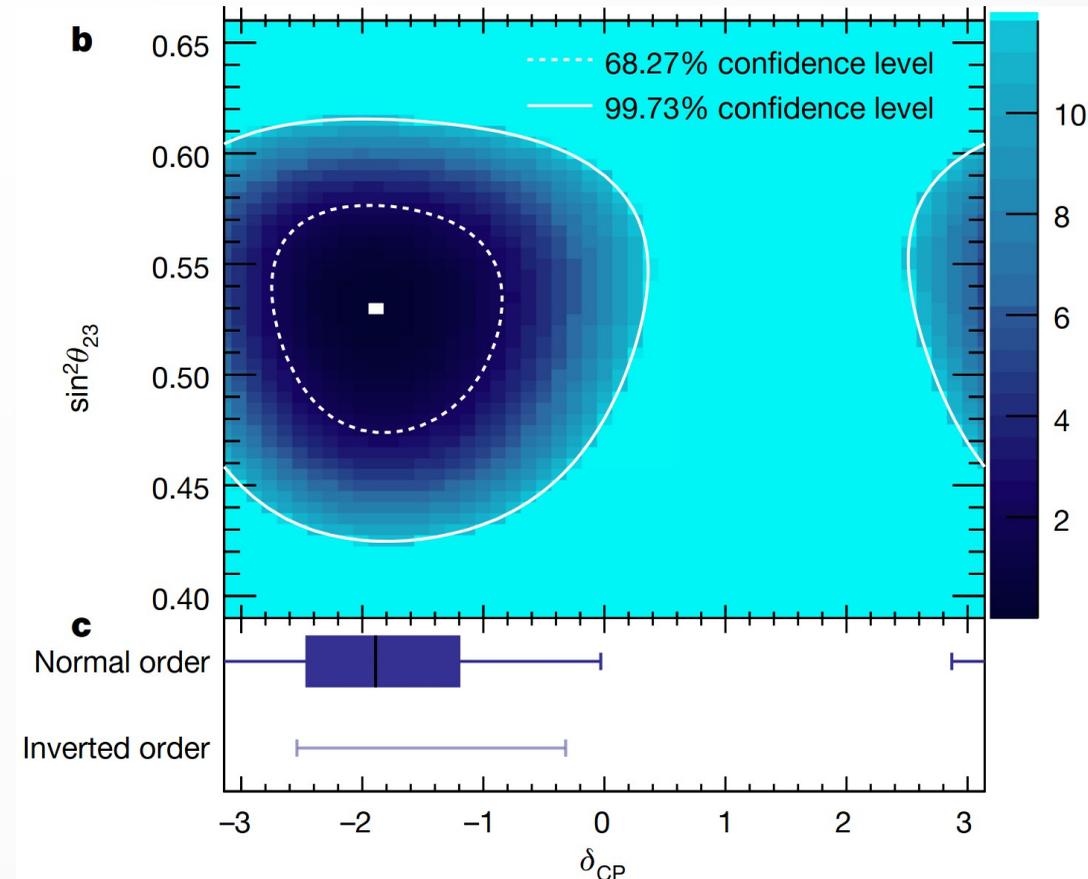


Results  
presented  
at Neutrino  
2016



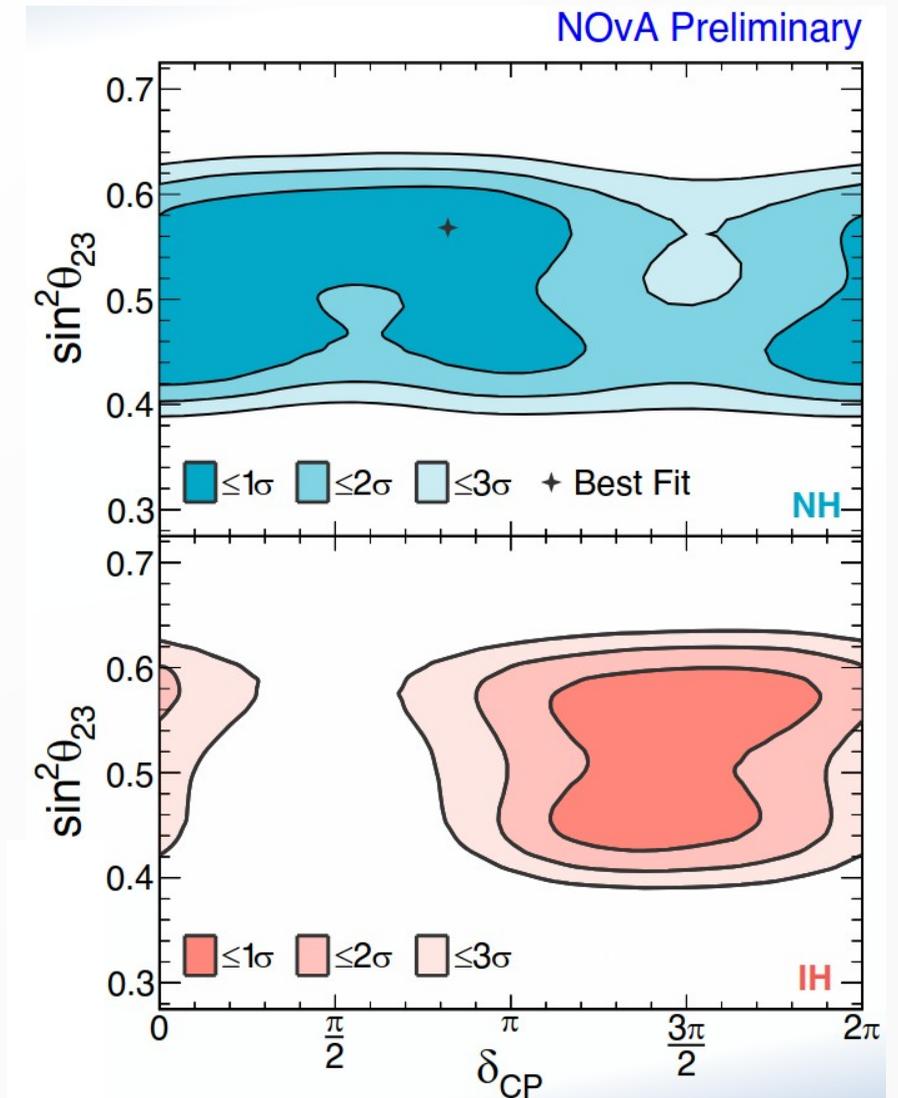
# CP violation search (history)

- In 2020 T2K excluded CP symmetry conservation at 95% confidence level.
- Preference of  $\delta_{CP}$  value close to maximal CP violation ( $-\pi/2$ )
- Posterior probability of the normal mass hierarchy reported to be 89%.
- Results published in the first T2K's Nature paper.

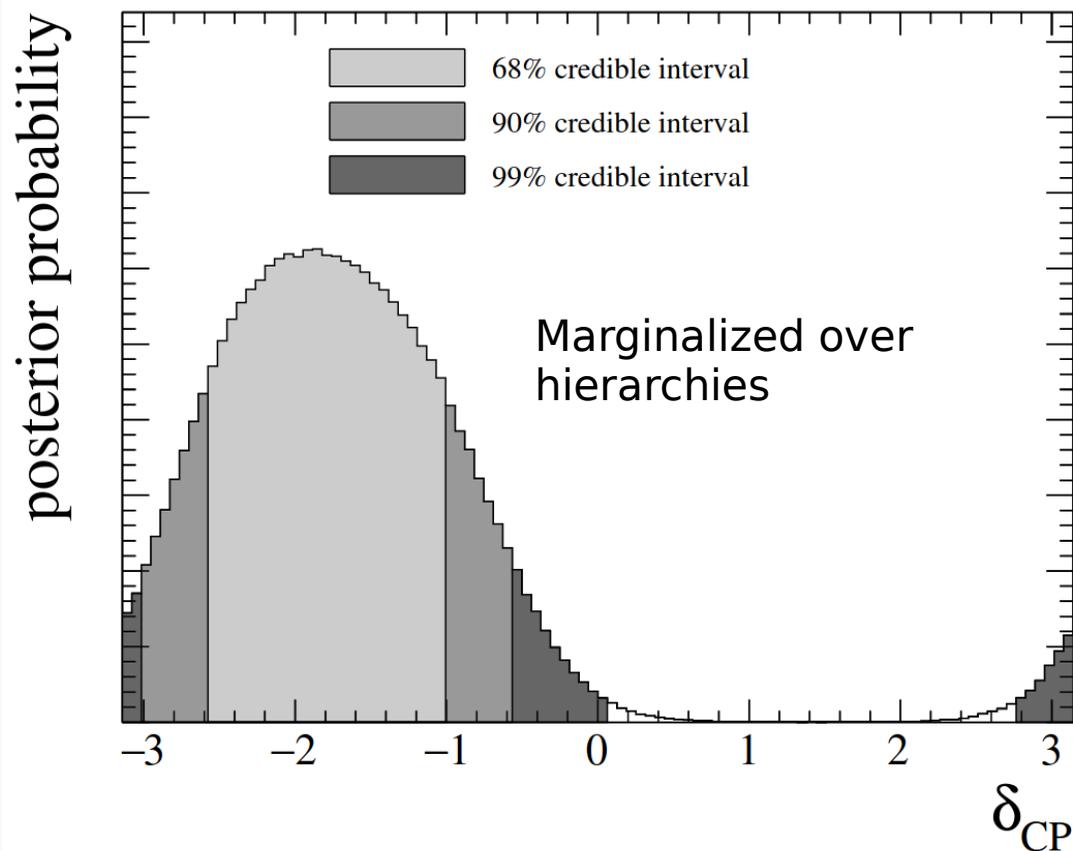


# CP violation search (history)

- At the same time NOvA experiment was reporting quite different results!
- Best fit value for  $\delta_{CP} = 0.82\pi$  (normal hierarchy), which was outside of T2K's  $3\sigma$  confidence interval.
- The tension between both experiments became apparent!



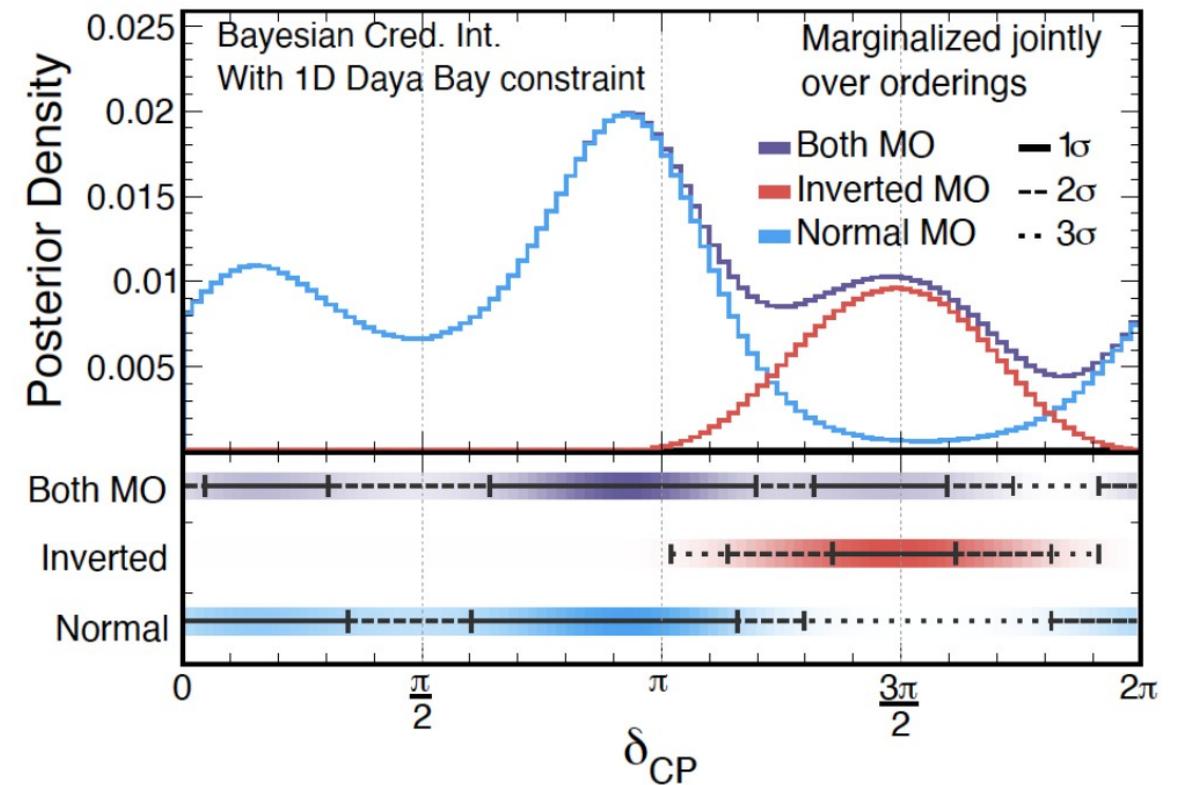
# CP violation search (current status of the independent analyses)



T2K oscillation analysis 2023  
CP conservation excluded at 90%  
confidence level

NuFACT 2025 talk by  
Jianming Bian

NOvA Preliminary



NOvA oscillation analysis 2024  
Highest posterior density close  
to the CP conserving value of  $\delta_{CP}$  29

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- Introduction: flavor-mass mixing, neutrino oscillations
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# Towards the joint T2K-NOvA analysis

## T2K and NOvA collaborations to produce joint neutrino oscillation analysis

January 30, 2018

The NOvA and T2K Collaborations are working towards the formation of a joint working group to enhance the measurements of neutrino oscillation parameters made by each Collaboration individually. **The projected timescale of the NOvA-T2K working group is for production of a full joint neutrino oscillation analysis by 2021.**

# Towards the joint T2K-NOvA analysis

- Some of the significant challenges for the joint fit:
- Different MC generator (NEUT used by T2K, GENIE used by NOvA)
- Working group must develop a joint systematic model.
- How exactly the oscillation fit should be implemented?



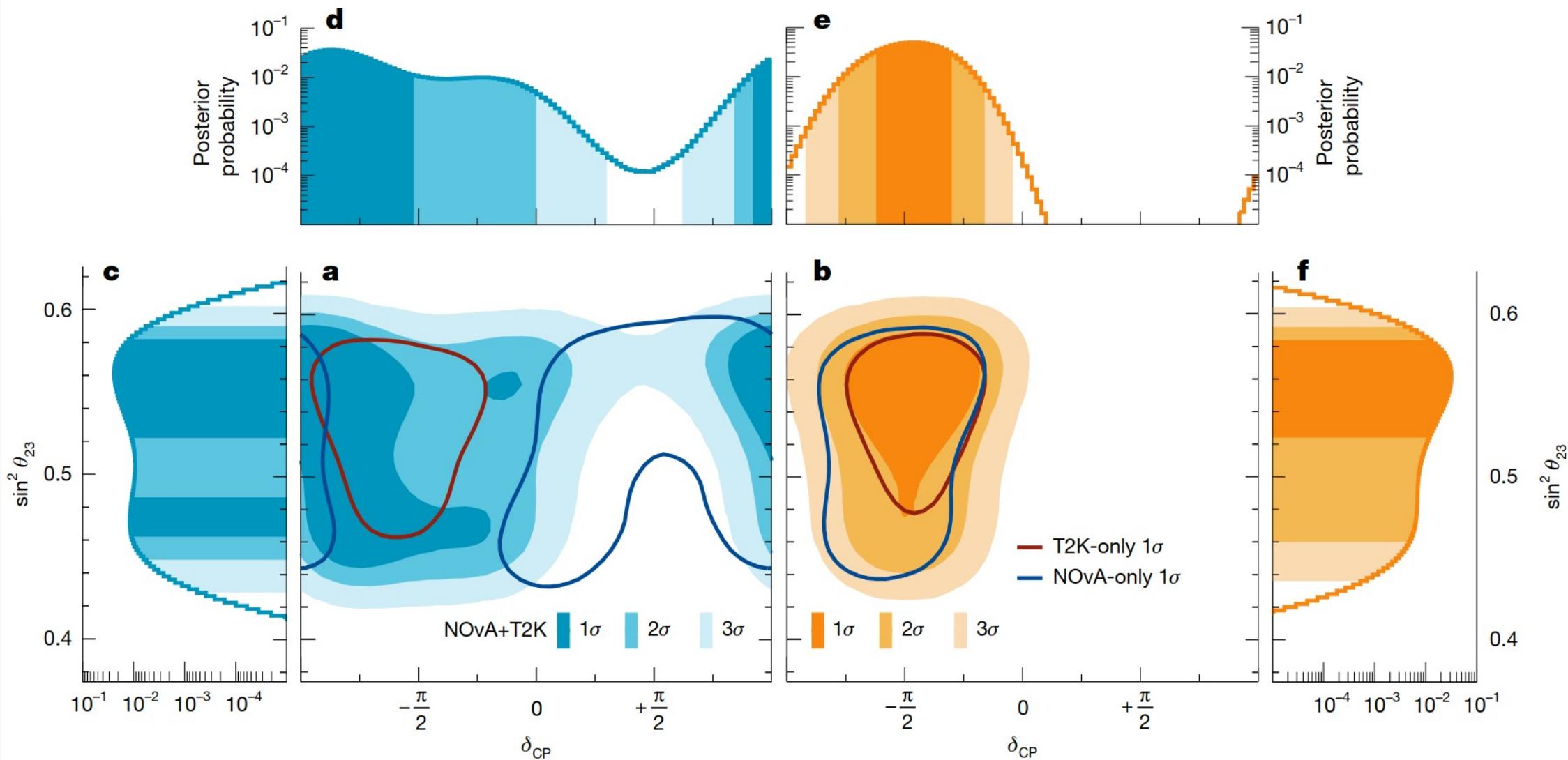
# Towards the joint T2K-NOvA analysis

- Some of the significant challenges for the joint fit:
- **Different MC generator (NEUT used by T2K, GENIE used by NOvA)**
- Working group must develop a joint systematic model.
- **How exactly the oscillation fit should be implemented?**
- **Simultaneous fit in both T2K and NOvA datasets, keep predictions from both MC generators in the respective samples.**

# Towards the joint T2K-NOvA analysis

- Some of the significant challenges for the joint fit:
- **Different MC generator (NEUT used by T2K, GENIE used by NOvA)**
- **Working group must develop a joint systematic model.**
- How exactly the oscillation fit should be implemented?
- **Identify possible correlations between T2K and NOvA samples, and implement them in the fit.**
- **Incorrect correlations might introduce more bias than neglecting the correlations!**

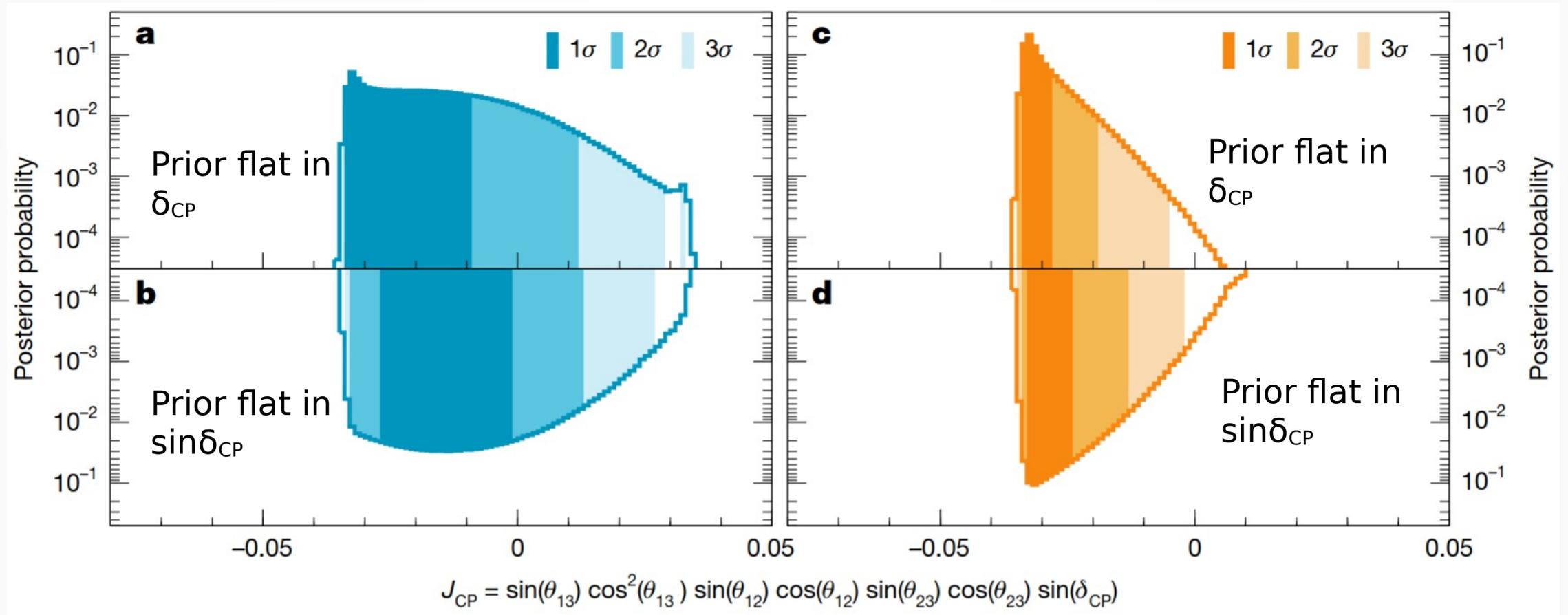
# $\sin^2\theta_{23}$ vs $\delta_{CP}$



Normal mass hierarchy

Inverted mass hierarchy

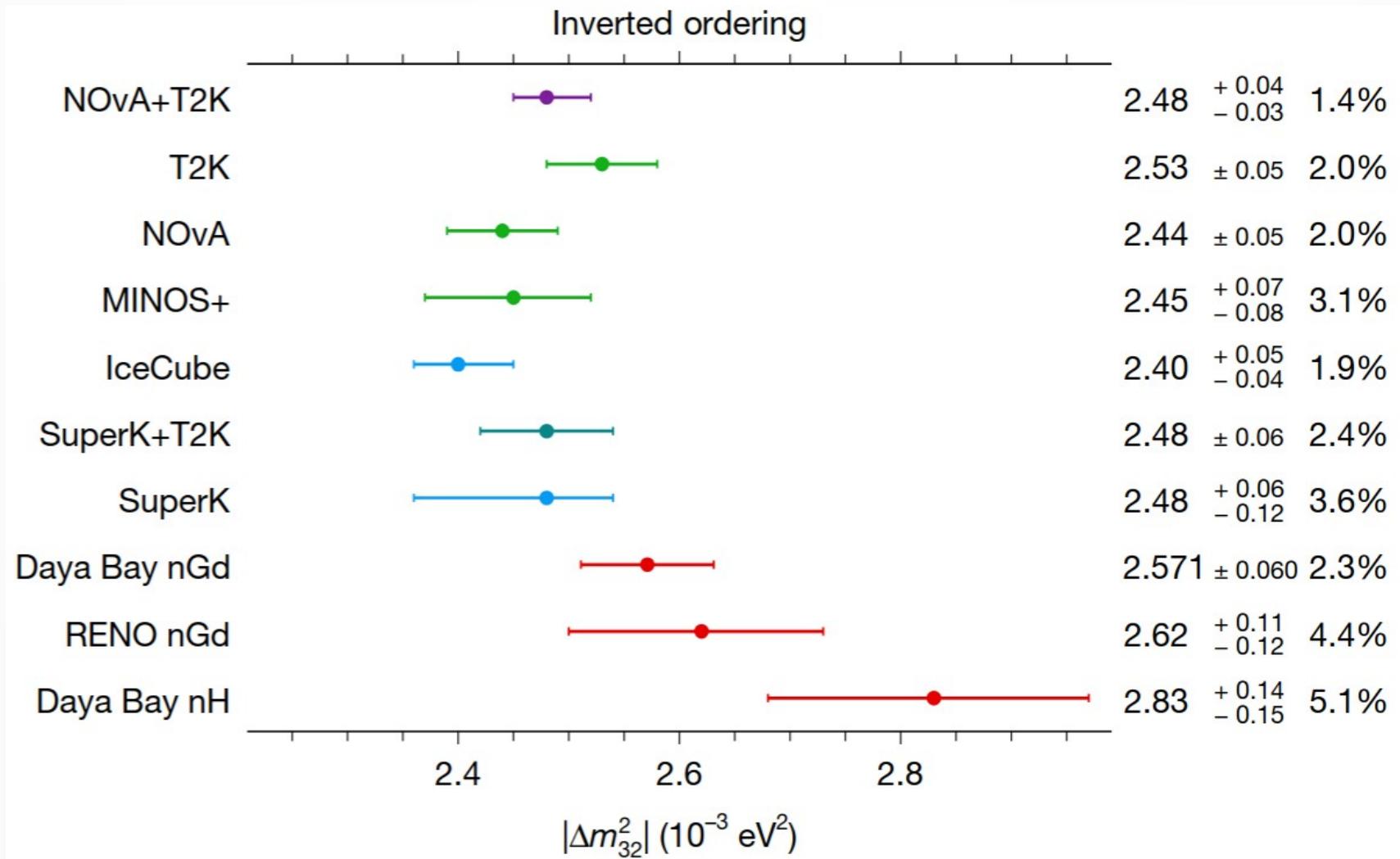
# Jarlskog invariant



Normal mass hierarchy

Inverted mass hierarchy

# $|\Delta m^2_{32}|$



Slight preference of the inverted mass hierarchy in the joint analysis. Posterior probability of 56.5%

# Summary

- First joint analysis for accelerator neutrino experiments!
- The smallest experimental uncertainty on  $|\Delta m^2_{32}|$ !
- No strong preference for either mass hierarchy.
- Assuming inverted hierarchy is true, the CP conservation is excluded at  $3\sigma$  CL.
- New generation of experiments will start taking beam data soon! Hyper-K ~2028, DUNE ~2031



**Hyper-Kamiokande**



DEEP UNDERGROUND  
NEUTRINO EXPERIMENT

# Backup

# Matter effects

Presence of electrons modifies the oscillation probabilities as compared to those in vacuum. CC scattering on electrons is possible only for electron (anti-)neutrinos. The probability for (anti-) $\nu_e$  appearance with the first order approximation of matter effects is expressed as:

$$\begin{aligned}
 P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) &\approx \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(A-1)^2} \sin^2[(A-1)\Delta_{31}] \\
 &+ \alpha \frac{J_0 \sin \delta_{CP}}{A(1-A)} \sin \Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}] \\
 &+ \alpha \frac{J_0 \cos \delta_{CP}}{A(1-A)} \cos \Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}] \\
 &+ \alpha^2 \cos^2 \theta_{23} \frac{\sin^2 2\theta_{12}}{A^2} \sin^2(A\Delta_{31})
 \end{aligned}$$

where

$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2$$

$$\Delta_{ij} = \Delta m_{ij}^2 L / 4E$$

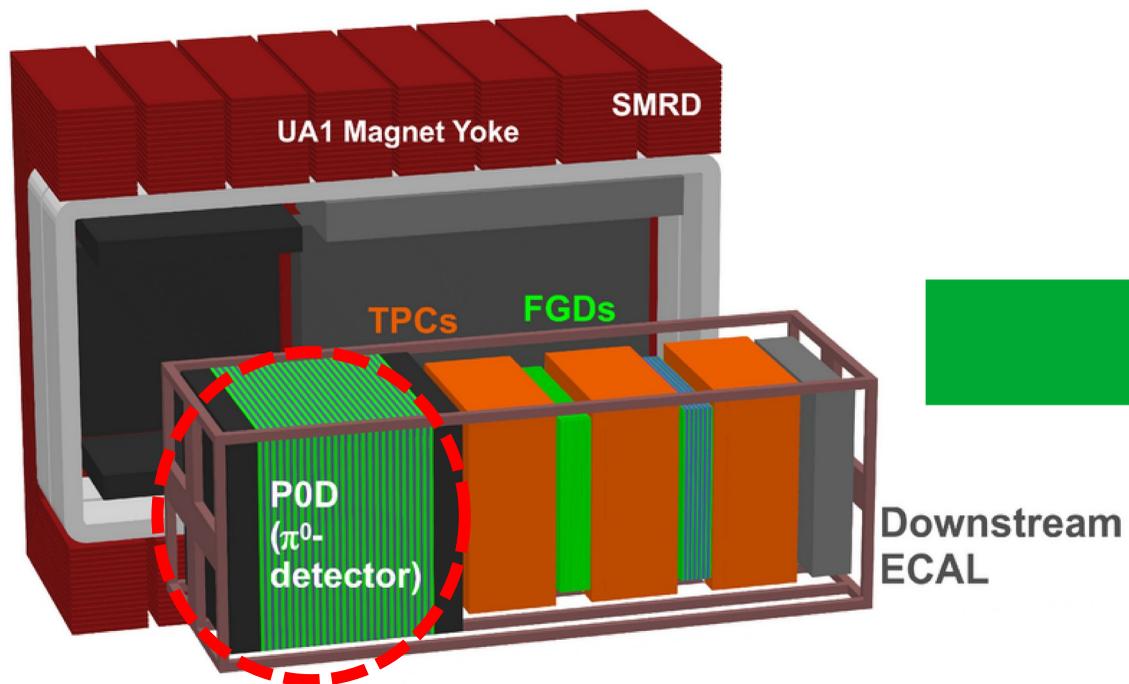
$$A = (-) 2\sqrt{2} G_F n_e E / \Delta m_{31}^2$$

$$J_0 = \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13}$$

Sign of the matter effects differs for neutrinos and antineutrinos.

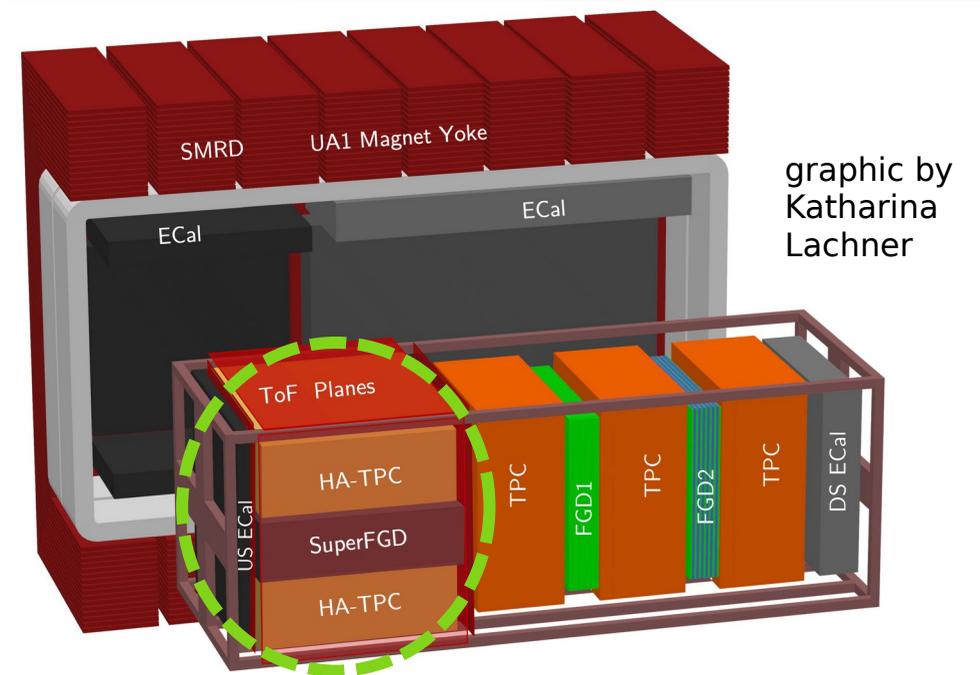
# ND280 upgrade

2010-2022



P0D –  $\pi^0$  detector built of scintillator, water, brass and lead layers

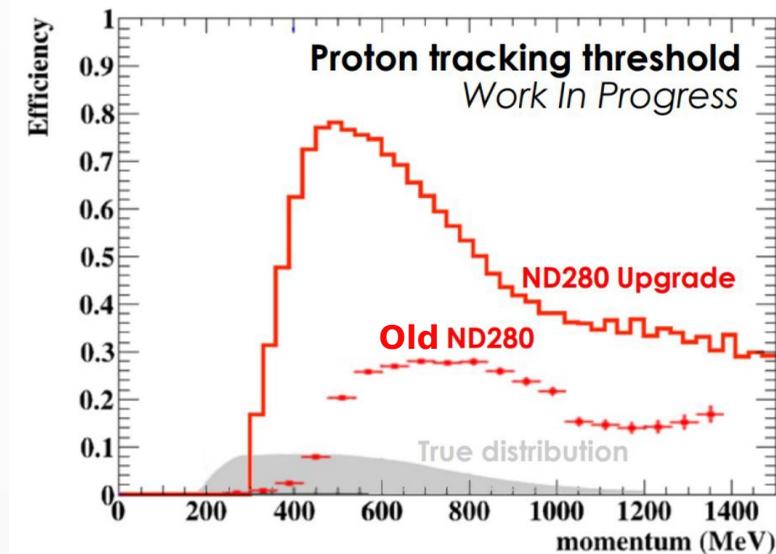
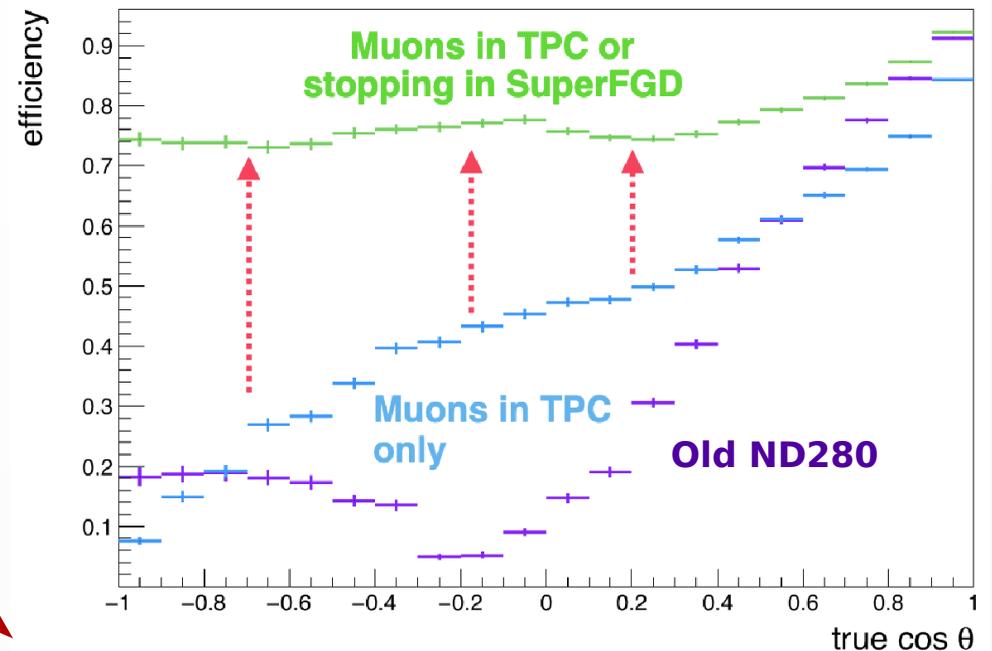
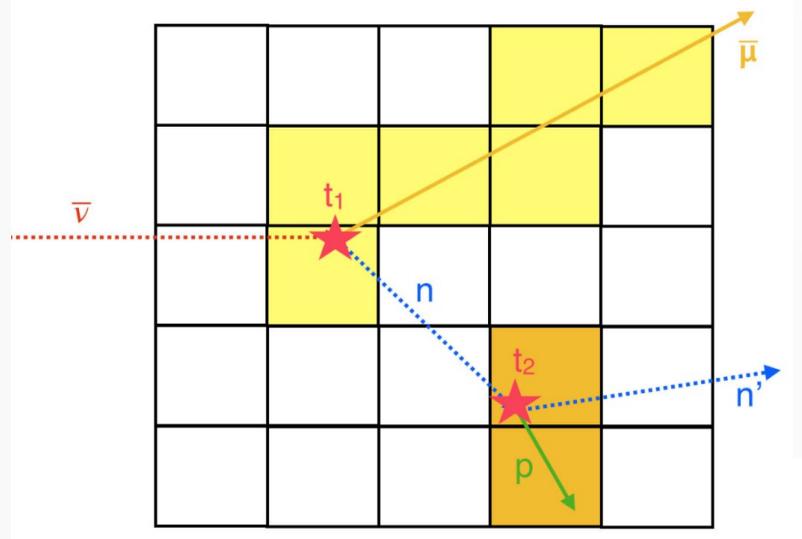
Completed in May 2024



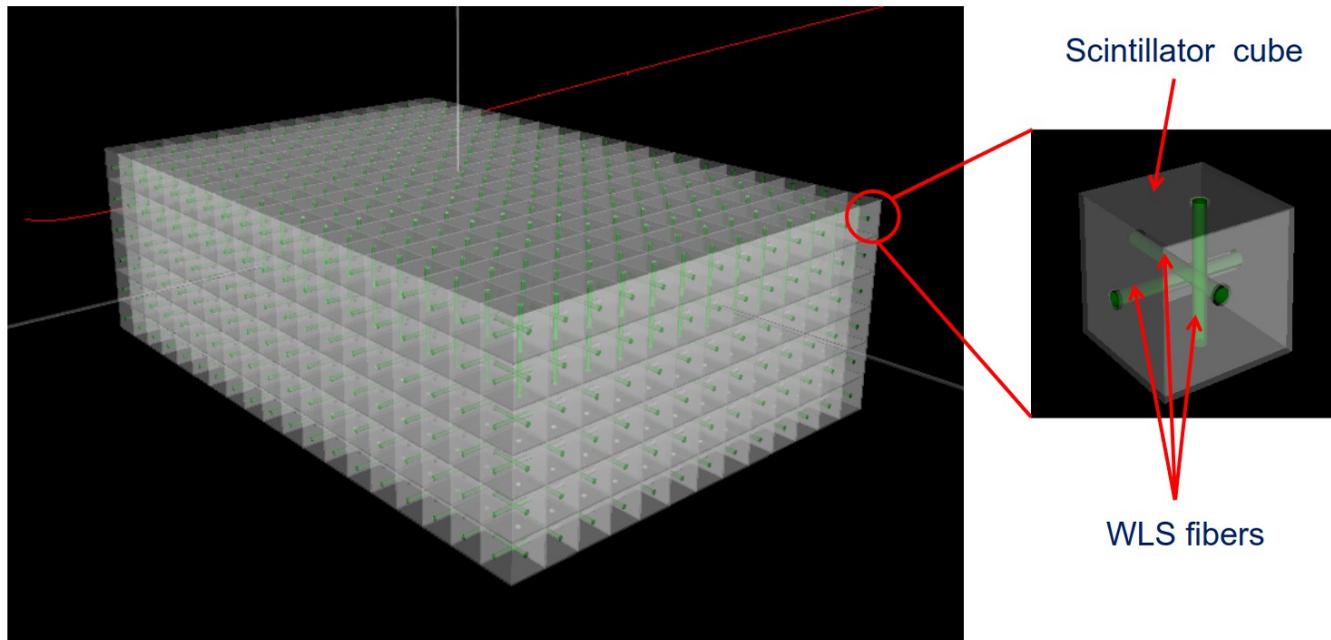
**Super-FGD,  
High-Angle TPCs,  
Time of Flight Planes**

# Upgraded ND280 performance

- Improved muon angular acceptance
- Lower threshold for proton tracking
- Neutron detection via proton recoil. Neutron energy estimation with time-of-flight.



# SuperFGD



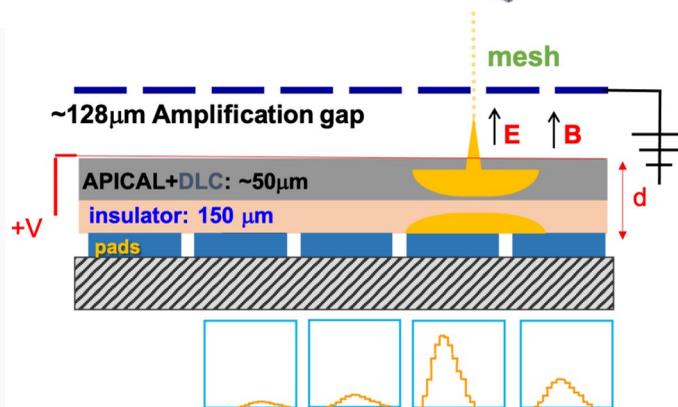
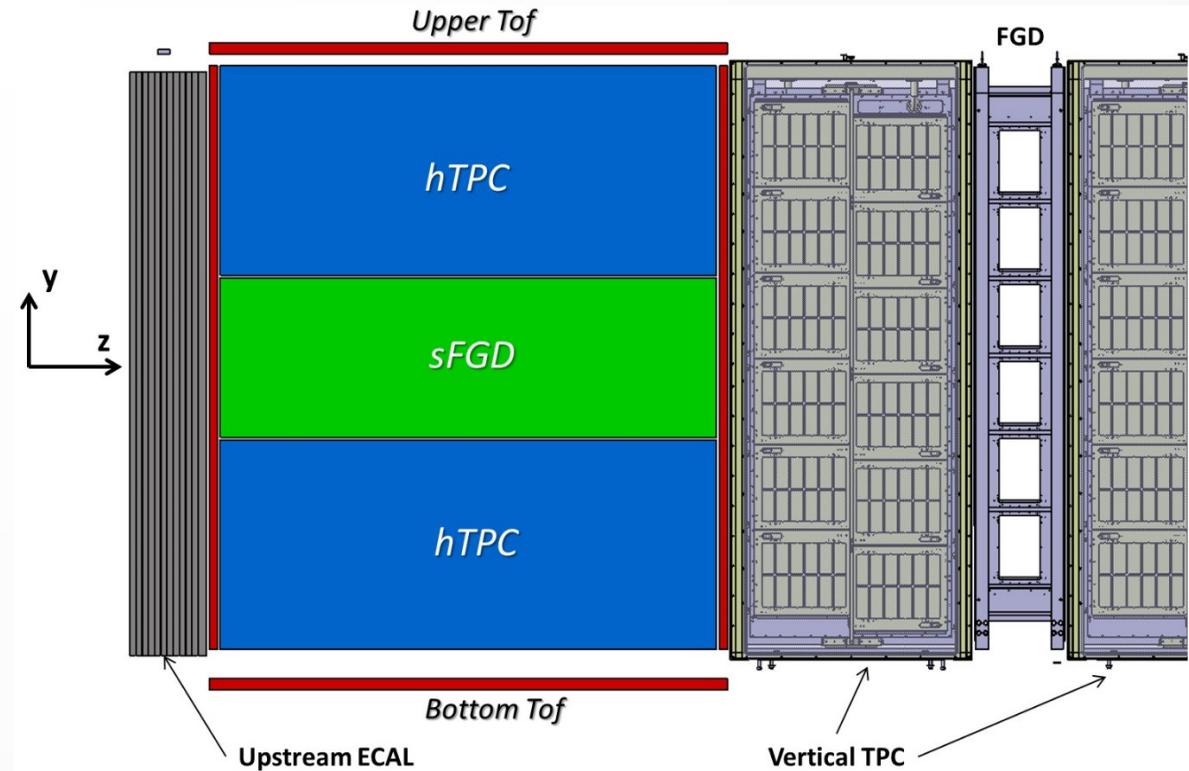
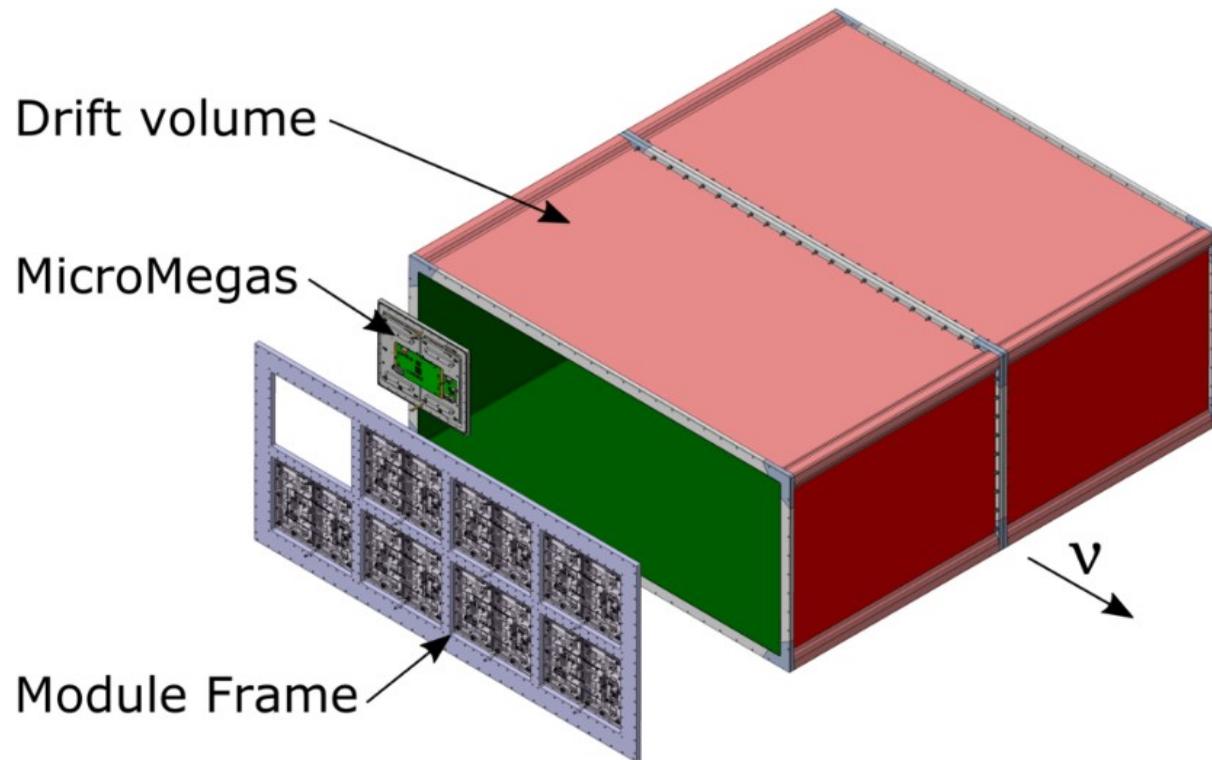
Schematic concept of the SuperFGD structure.

- The size of each cube is  $1 \times 1 \times 1 \text{ cm}^3$ .
- The active part of SuperFGD is  $192 \times 192 \times 56 \text{ cm}^3$ .
- Altogether  $\sim 2\text{M}$  cubes.

SuperFGD layers assembly at J-PARC

ND280 upgrade design  
report: [arXiv:1901.03750](https://arxiv.org/abs/1901.03750)

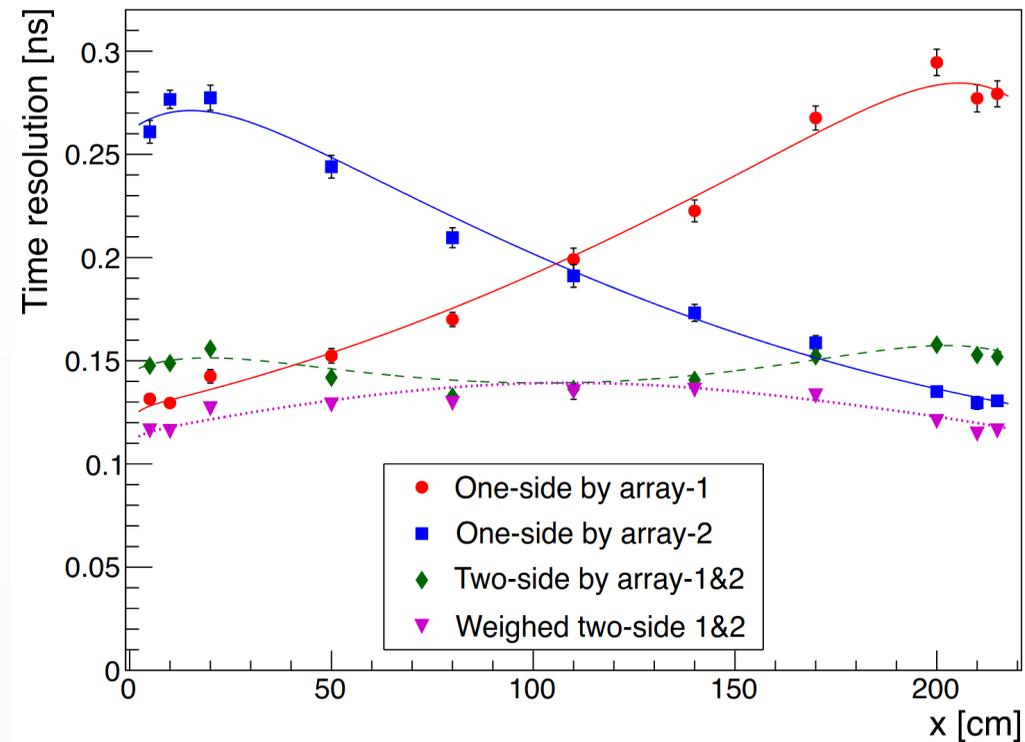
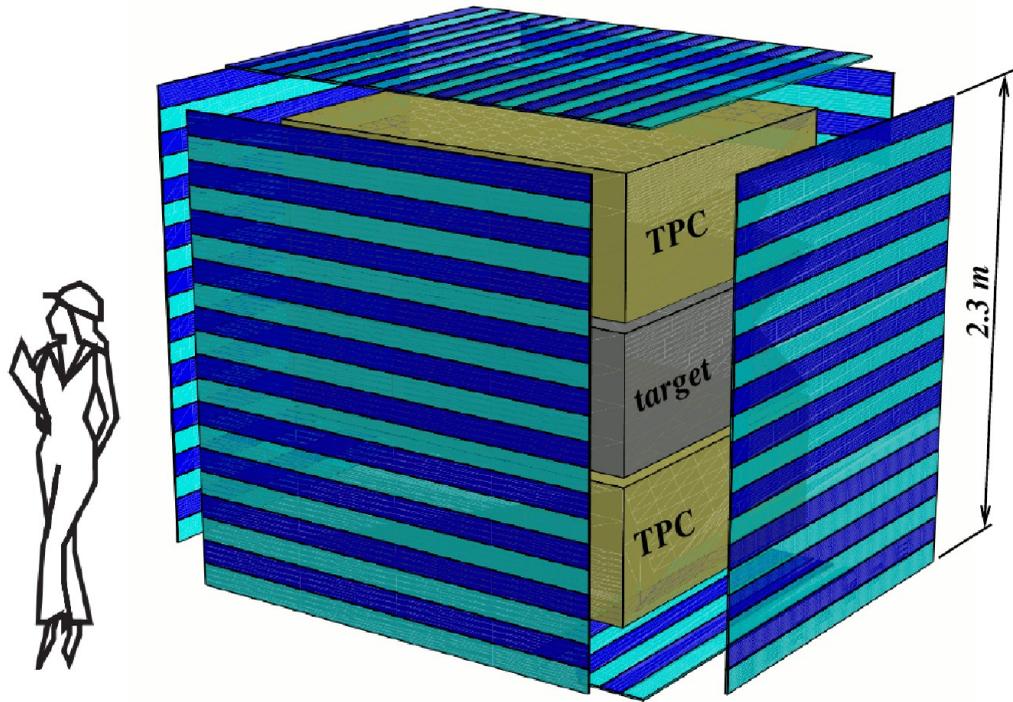
# High angle TPCs



- Bottom and Top HATPC - nearly  $4\pi$  acceptance of tracks starting in SuperFGD.
- 8 Encapsulated Resistive Anode Micromegas (ERAM).
- Tracks reconstruction resolution of  $200\text{-}800\mu\text{m}$ .

# ToF Planes

- Time-of-flight system designed to measure precisely the crossing time of charged particles in ND280.
- Time resolution  $\sim 0.15$  ns

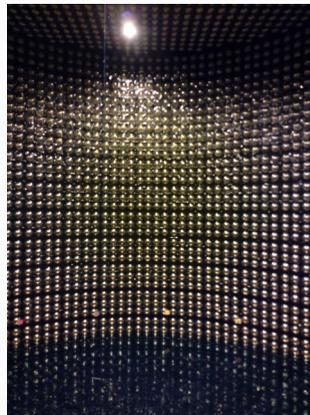
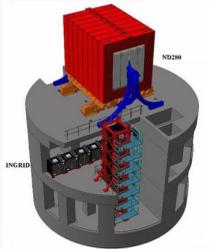


ToF modules tested at CERN

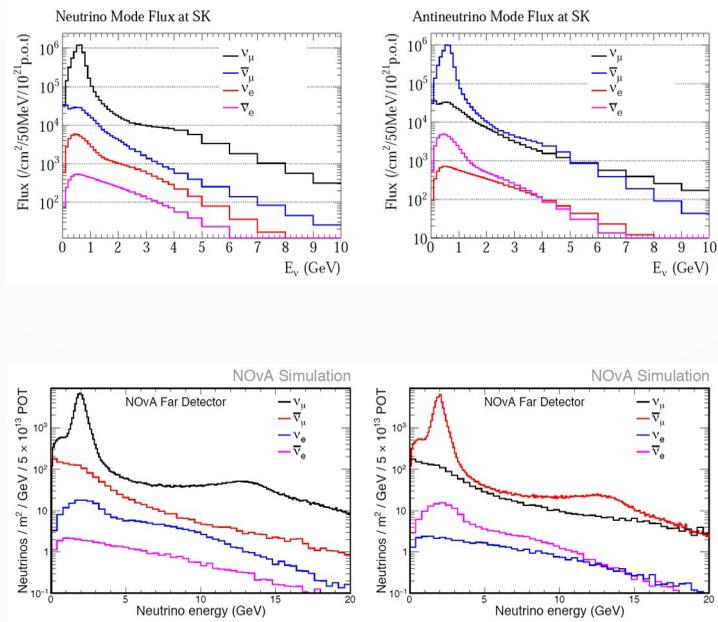
arXiv:2109.03078

# Possible correlations

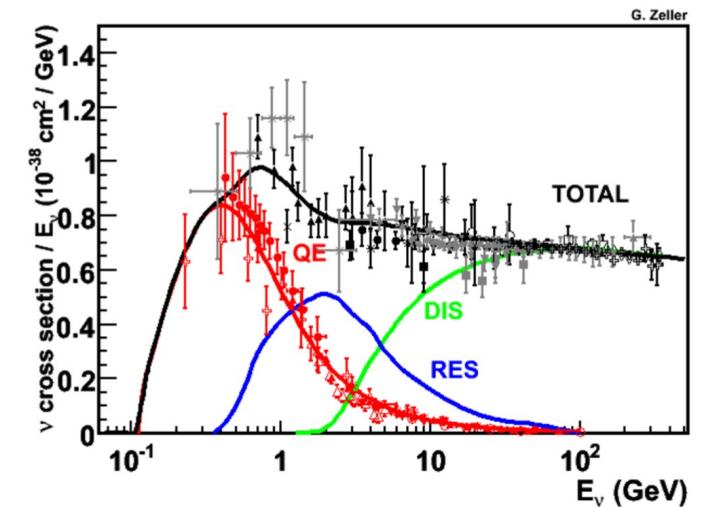
## Detector systematic uncertainties



## Flux predictions

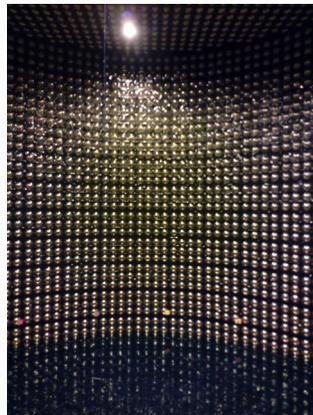
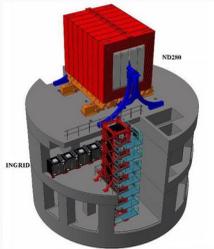


## Neutrino interaction modeling

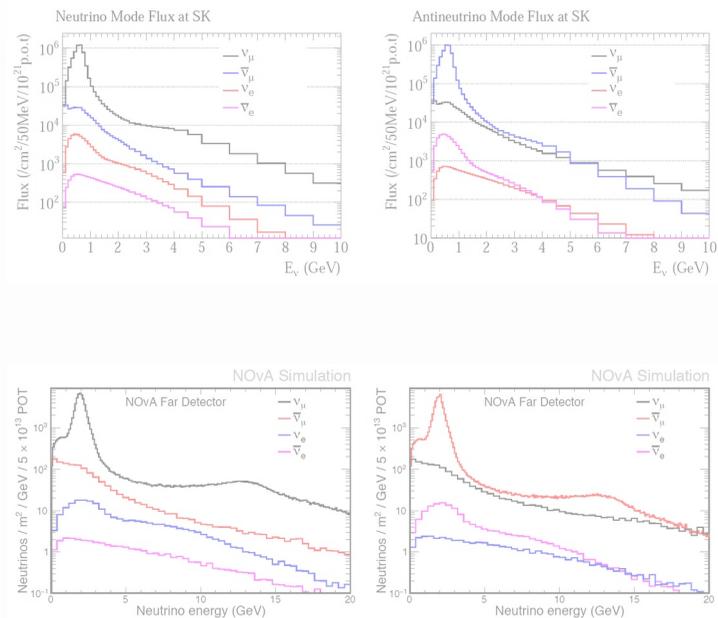


# Possible correlations

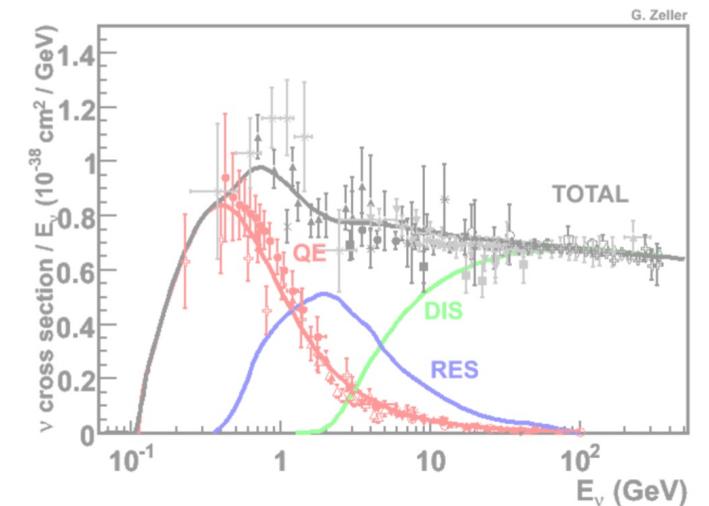
## Detector systematic uncertainties



## Flux predictions



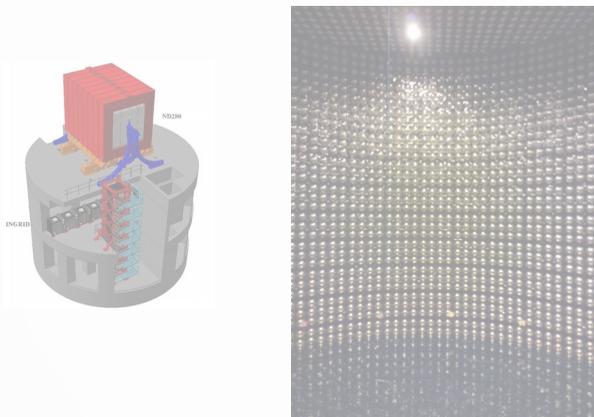
## Neutrino interaction modeling



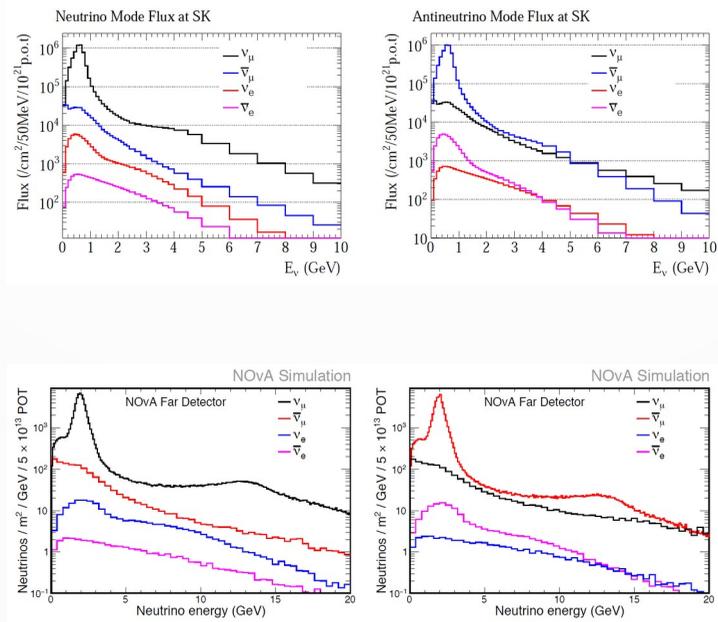
Different detection techniques and different methods of neutrino energy reconstruction. Correlations negligible.

# Possible correlations

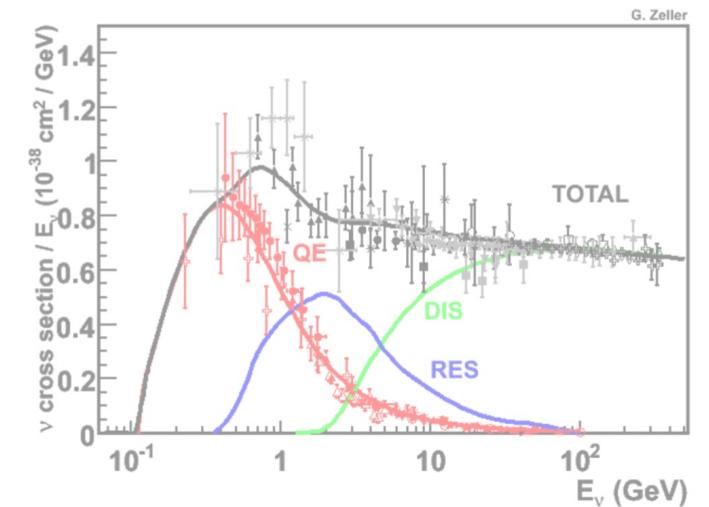
## Detector systematic uncertainties



## Flux predictions



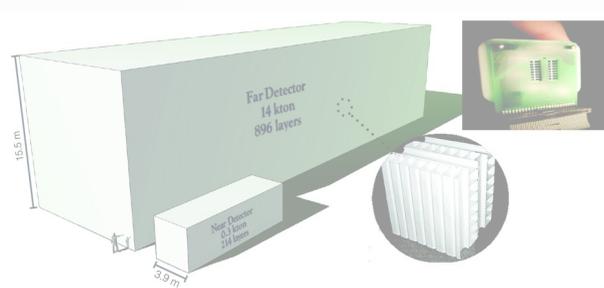
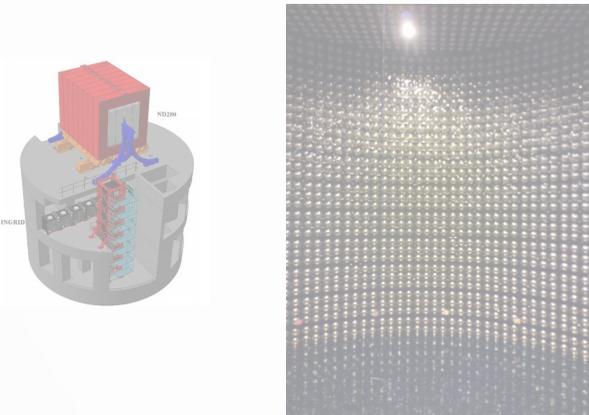
## Neutrino interaction modeling



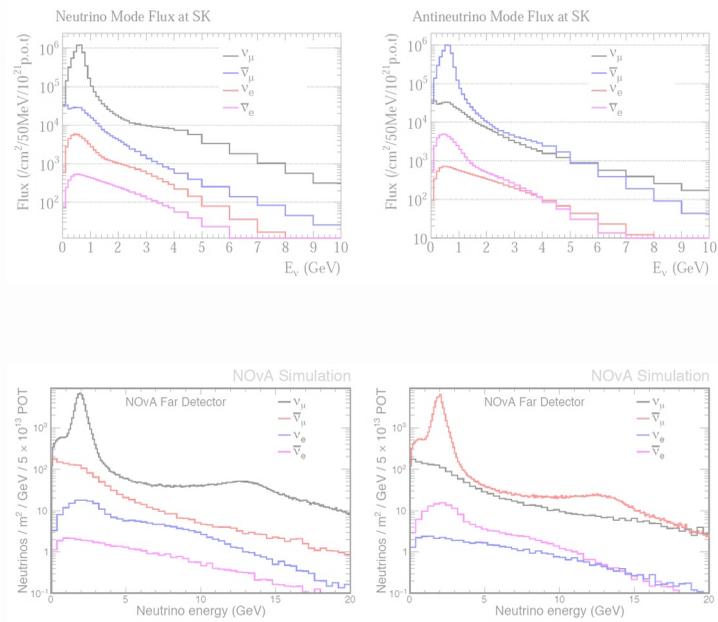
Different neutrino energies and different external constraints.  
Correlations negligible.

# Possible correlations

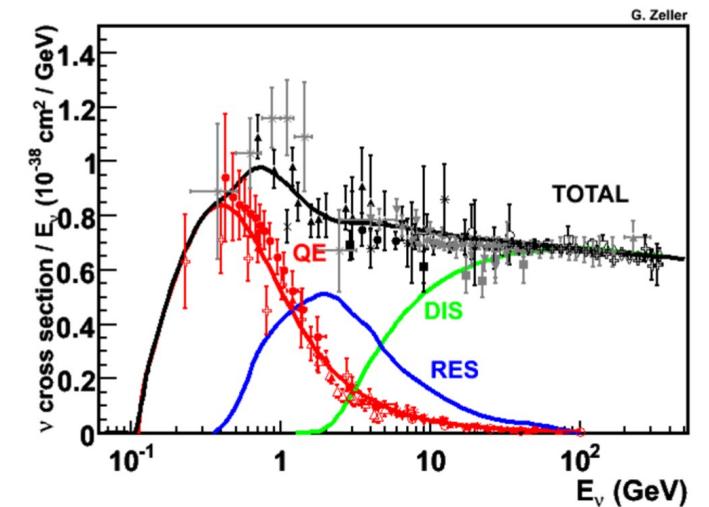
## Detector systematic uncertainties



## Flux predictions



## Neutrino interaction modeling



Correlations expected to be the most significant. However with different generators, different nuclear targets and energies the estimation of the correlations is tricky!

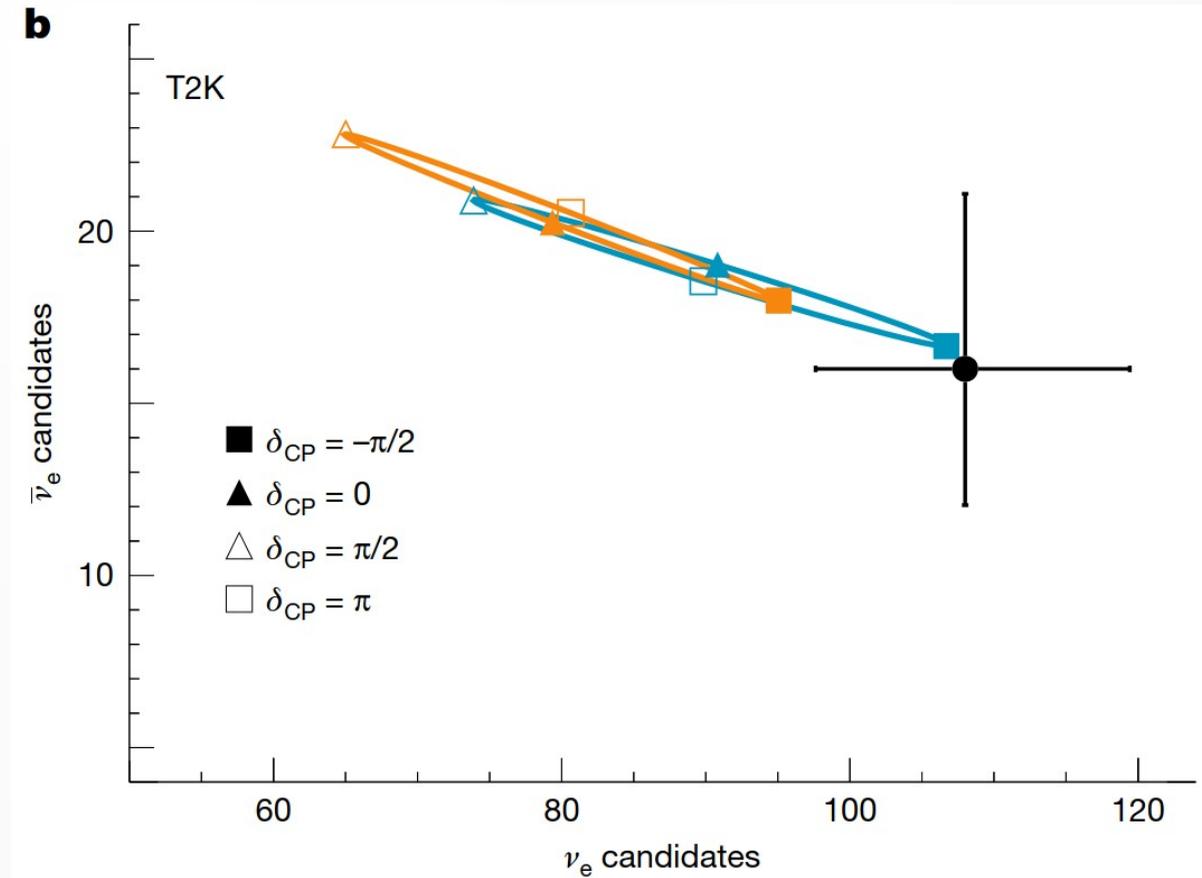
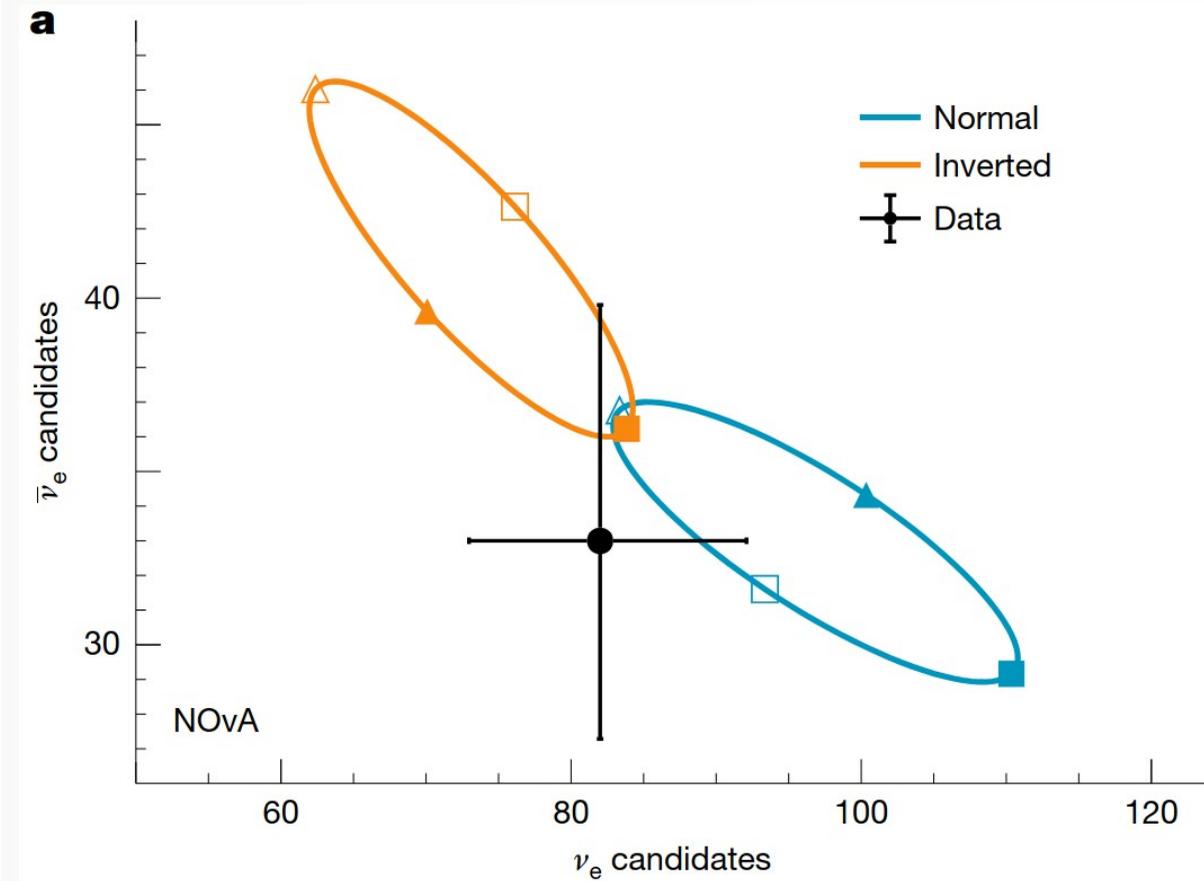
# Tackling the correlations

- First, the single systematic parameters of NOvA and T2K were probed to check which have the largest impact on the oscillation fit.
  - Largest change comes from  $\nu_e$ /anti- $\nu_e$  normalization.  
Identical treatment in T2K and NOvA, correlation necessary.
- Nightmare parameters study – suppose there are hidden correlations between multiple model systematic uncertainties, which introduce bias in the fit of a given oscillation parameter.
  - Consider the impact comparable to that of statistical errors.

# Tackling the correlations

- Prepare augmented models with nightmare parameters included.
  - Construct simulated pseudo-datasets with the nightmare parameters increased by one standard deviation.
  - 3 oscillation fits with nightmare parameters (1) fully correlated between the experiments, (2) fully anticorrelated and (3) uncorrelated. The second case yields a large bias.
- **Significant bias introduced not by neglecting correlations, but by adding incorrect correlations.**

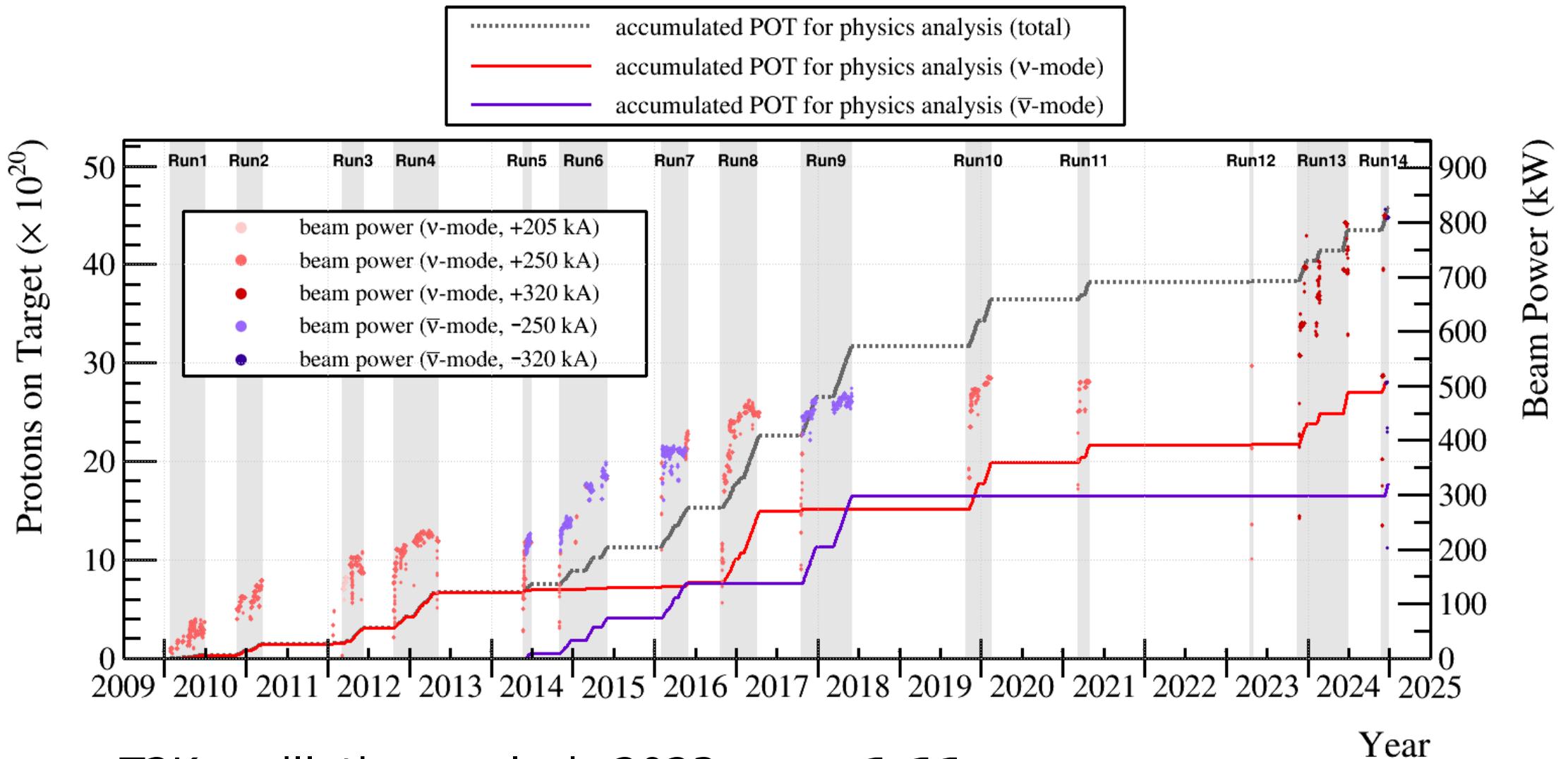
# Sensitivity to mass ordering and $\delta_{CP}$



# Comparison of future and current experiments

	T2K	NOvA	DUNE	Hyper-K
Baseline [km]	295	810	1300	295
Beam energy peak [GeV]	0.6	2	2.5-3	0.6
setup	off-axis	off-axis	on-axis	off-axis
Near Detector	Multi-purpose magnetized (FGD, TPC, ECal)	Extruded plastic cells filled with liquid scintillator	Multi-purpose (LAr TPC, magnetized HPGAr TPC w/ ECal, scint tracker)	Multi-purpose magnetized (SuperFGD, TPC, ECal) + Intermediate
Far Detector	Water Cherenkov 50 kton	Extruded plastic cells filled with liquid scintillator 14 kton	Liquid Argon TPC 4 × 17 kton	Water Cherenkov 260 kton
Expected sensitivity to CPV	will reach $>3\sigma$	will reach $>2\sigma$	will reach $>5\sigma$	will reach $>5\sigma$
timescale	2010-2026	2014-2027	~2031-	~2028-

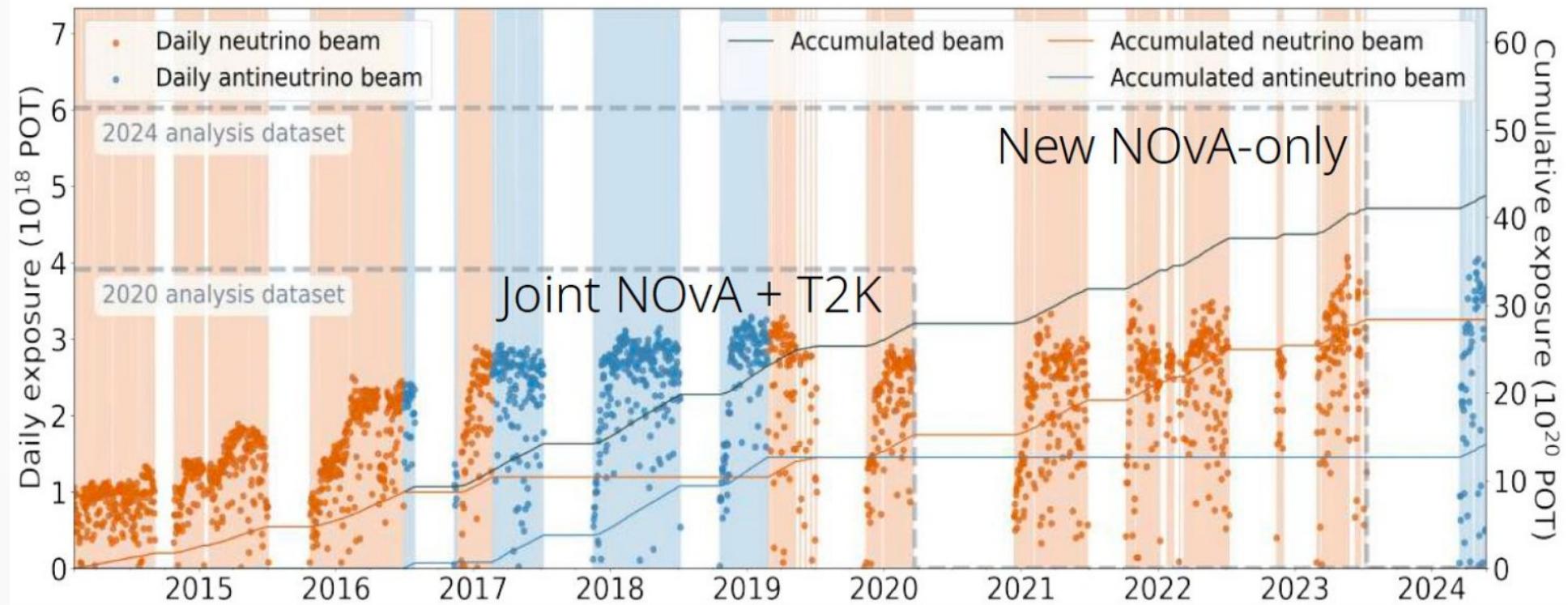
# Accumulated POT (T2K)



T2K oscillation analysis 2023: **runs 1-11**

NOvA+T2K joint oscillation analysis: **runs 1-10**

# Accumulated POT (NOvA)



- 2014-2023: 10 years of beam to NOvA
- Neutrino beam data:  $26.6 \times 10^{20}$  Protons on Target (POT), (+96%)
- Antineutrino data:  $12.5 \times 10^{20}$  POT

# Upgrade impact on the CPV search in T2K

