CP violation in the neutrino sector: Recent long-baseline experiments results

Grzegorz Żarnecki

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NCBJ

Outline

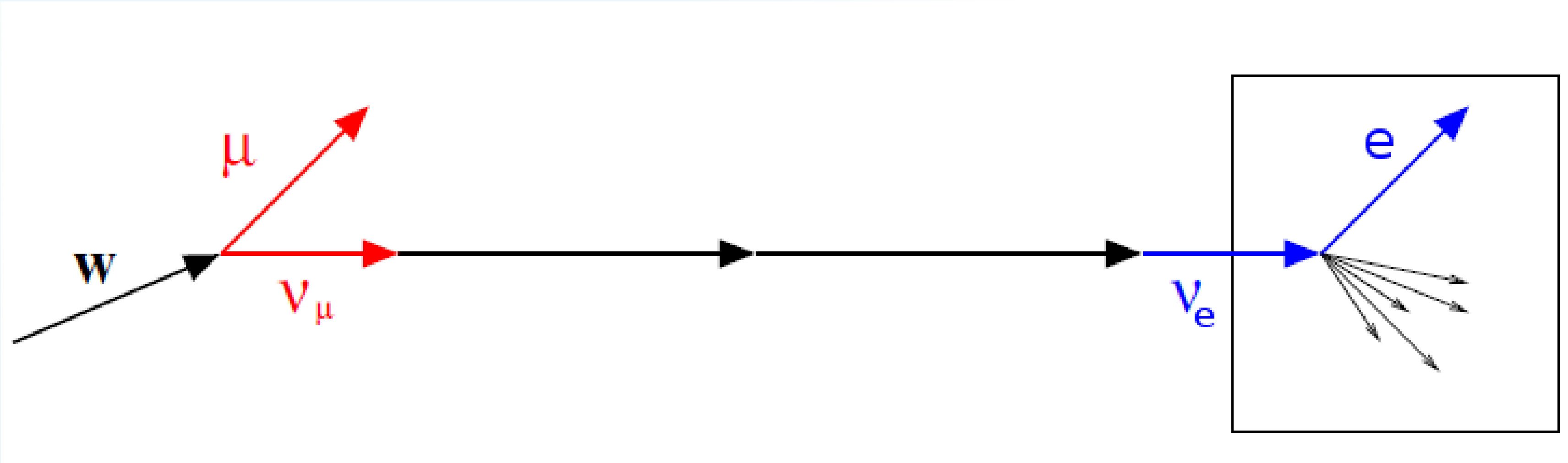
- Introduction: CP violation, neutrino oscillations
- Current leading long-baseline experiments: T2K and NOvA
- Future experiments: DUNE and Hyper-Kamiokande
- Summary

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 in the Universe.
  - Discovered in quark sector.

- In neutrino sector it may be manifested in different oscillation probabilities (for neutrinos and antineutrinos).

Neutrino oscillations: basic idea



- The flavour states ν_α, are superposition of mass eigenstates ν_i:

$$|\nu_\alpha\rangle = \sum_{\mathrm{i}} \mathrm{U}_{\alpha\mathrm{i}} |\nu_{\mathrm{i}}\rangle$$

- ν_i are eigenstates of Hamiltonian and propagate for a time *t* as:

$$|\nu_{\mathrm{i}}(t)\rangle = e^{-iE_{\mathrm{i}}t} |\nu_{\mathrm{i}}(0)\rangle$$

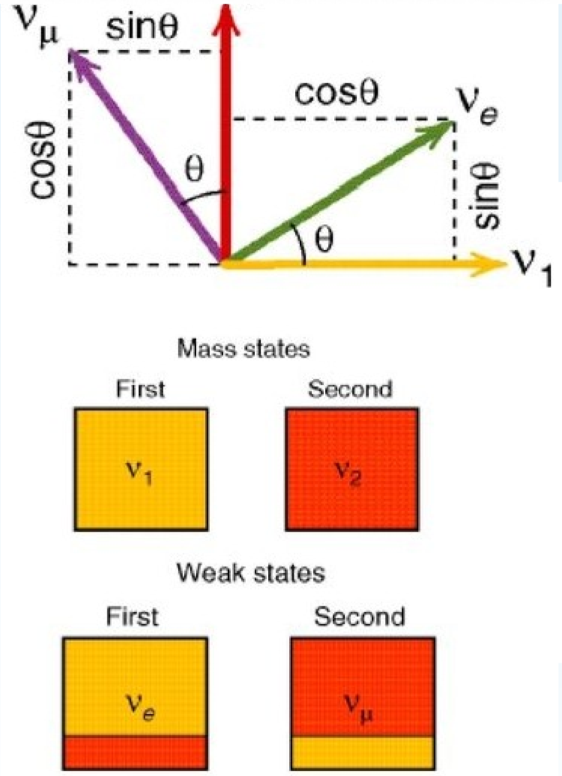
where $E_{\mathrm{i}} = \sqrt{p^2 + m_{\mathrm{i}}^2}$

(for vacuum)

Neutrino oscillations: two flavors approximation

- For two flavor approximation the probability of flavor conservation may be expressed as:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

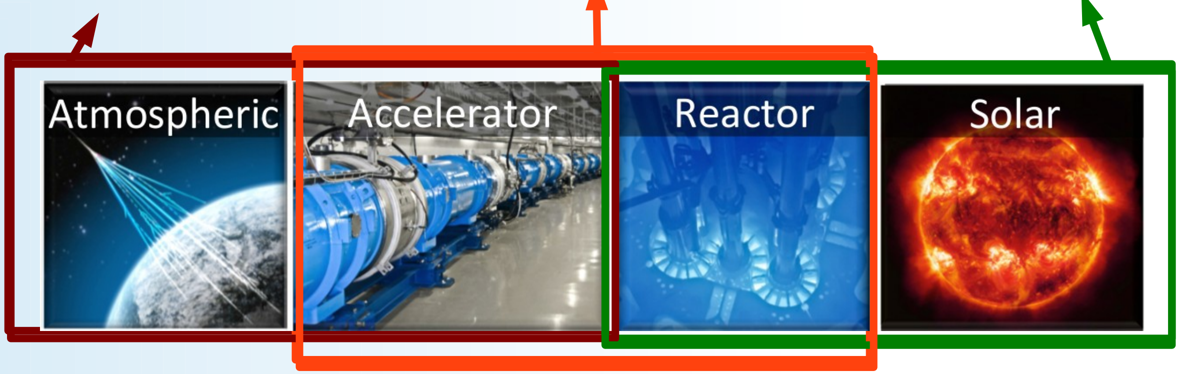


$$P(\nu_\mu \to \nu_\mu) = |\langle \nu_\mu(t)|\nu_\mu(0)\rangle|^2$$
$$= 1 - \sin^2 2\theta \sin^2\left(\frac{E_2 - E_1}{2}t\right)$$
$$\approx 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

Neutrino oscillations: flavor-mass mixing

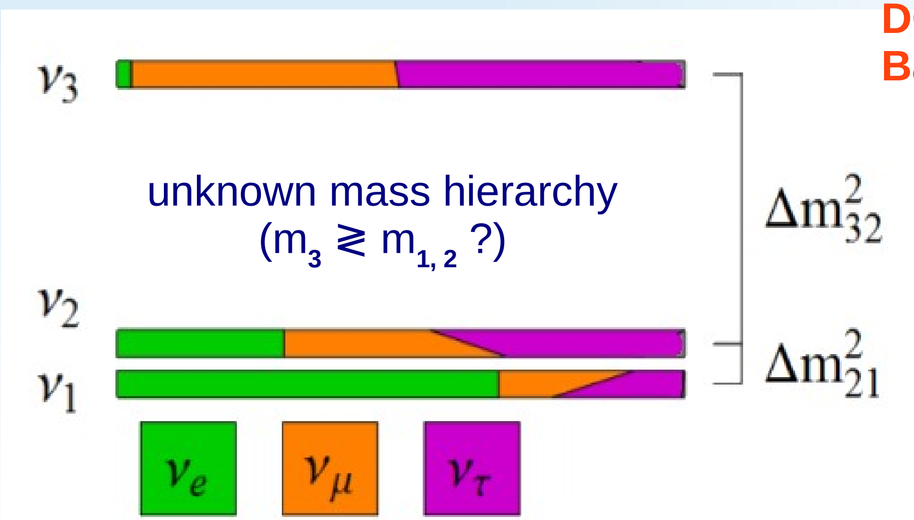
$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix}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

Super-K, K2K, MINOS, OPERA NOνA, T2K



Super-K, SNO, KamLAND

DChooz, RENO, Daya Bay, NOνA, T2K



- c_{ij}, s_{ij} – $\cos\theta_{ij}$, $\sin\theta_{ij}$
- θ_{ij} – mixing angles,
  δ_{CP} – CP violation (CPV) phase
- Long-baseline experiments are sensitive to Δm^2_{32}, θ_{23}, θ_{13} and δ_{CP}.

Three flavor $\nu_\mu \to \nu_e$ appearance probability

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

Leading including matter effect

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

CP conserving

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

CP violating

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

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

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

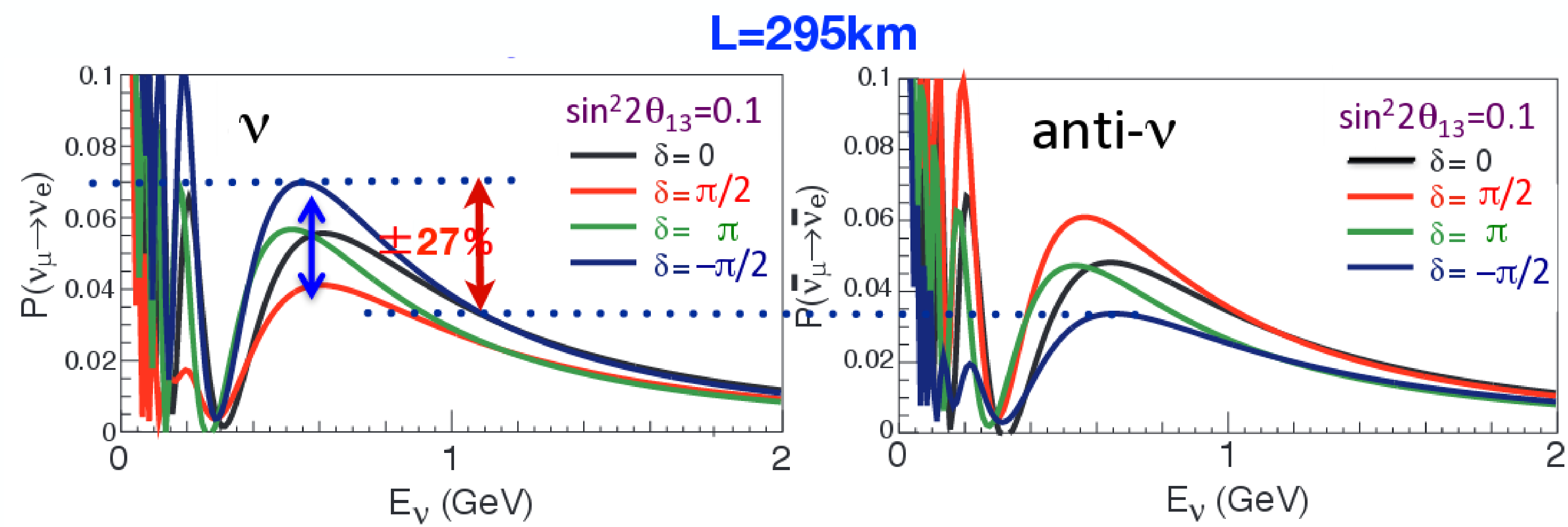
$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

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

replace δ_{CP} by $-\delta_{CP}$ and a by $-a$ for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$

The impact of CP violation

- If δ_{CP} = 0 or π then the CP symmetry is conserved. $P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ (in vacuum)
- If δ_{CP} = -π/2 then $P(\nu_\mu \rightarrow \nu_e) > P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- If δ_{CP} = +π/2 then $P(\nu_\mu \rightarrow \nu_e) < P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



Matter effects included

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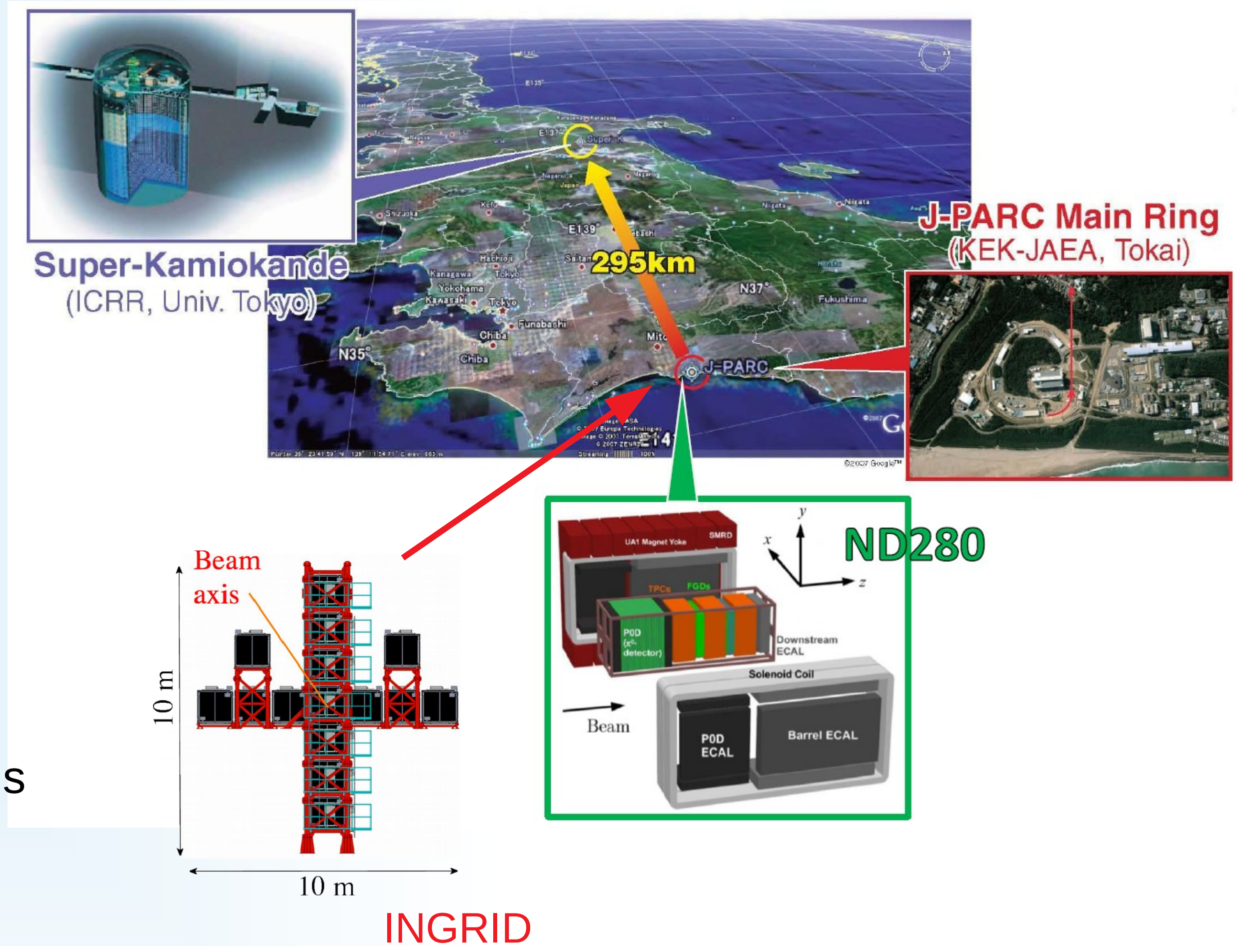
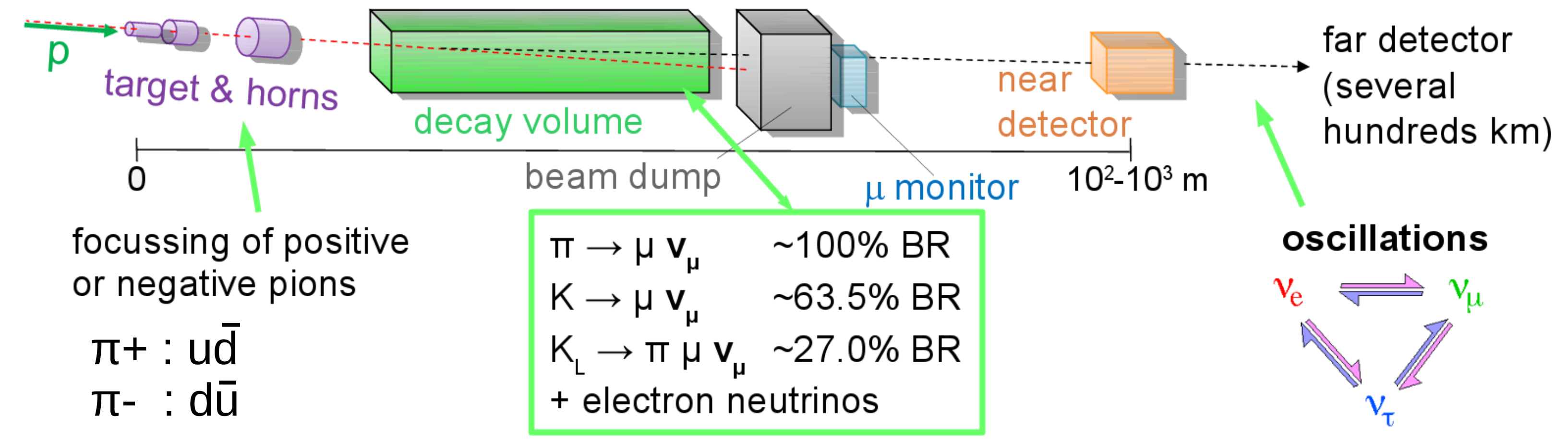
T2K experiment

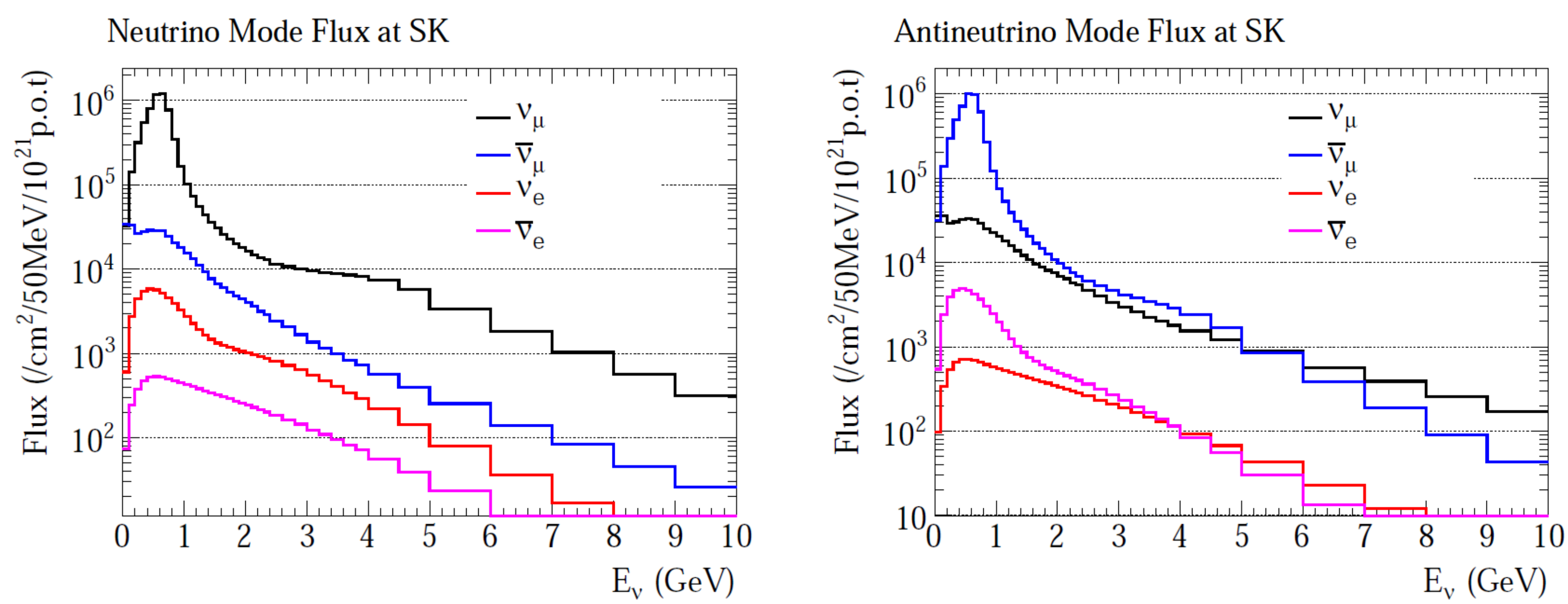
- T2K is a long-baseline neutrino experiment. Two near detectors (INGRID, ND280) are used to study beam ~280 m from the source in J-PARC.
- Super-Kamiokande is used as the far detector.
- Started taking data in 2010, ν_e appearance discovered in 2013.
- Active contribution of Warsaw Neutrino Group (NCBJ, UW & PW):
  - Cross-section measurements
  - ND280 upgrade
  - Data taking and detector expert shifts
  - ND280 input to oscillation analysis
  - Reflectivity measurements at the PMTs in Super-K
  - Studies on oscillation analysis – expanding Super-K FV



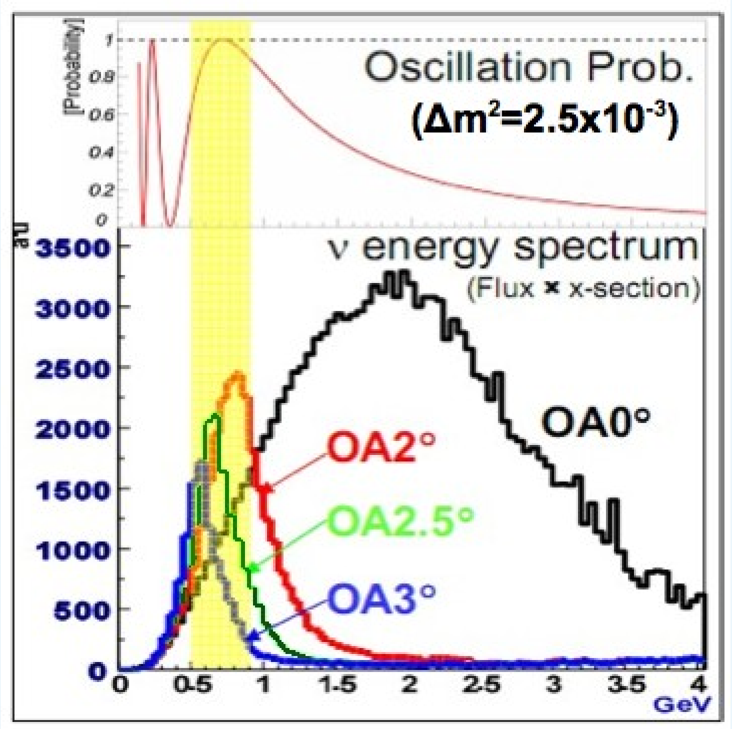
T2K beam

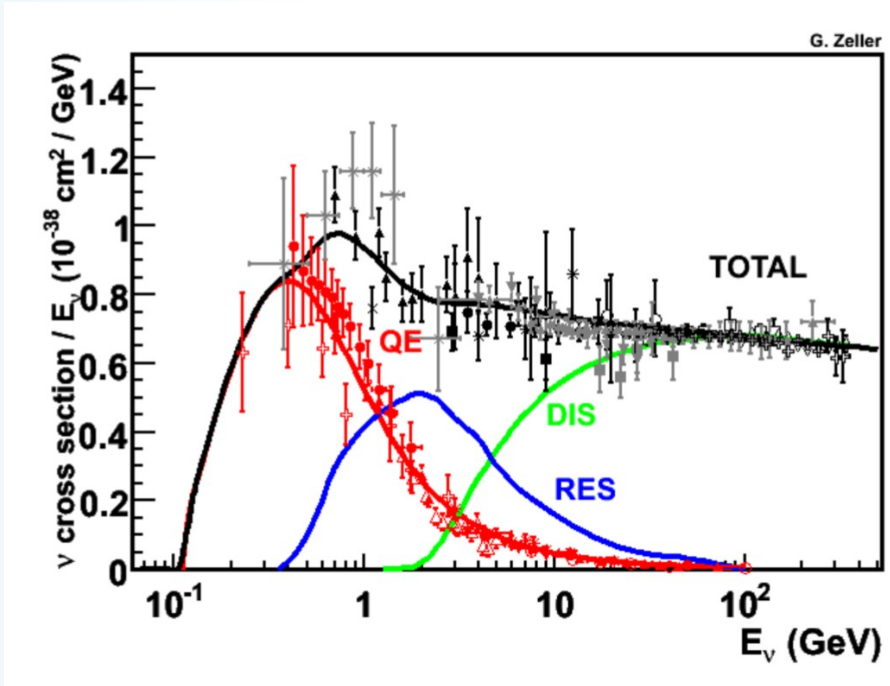


Beam may be used in FHC (neutrino) mode or RHC (anti-neutrino) mode.



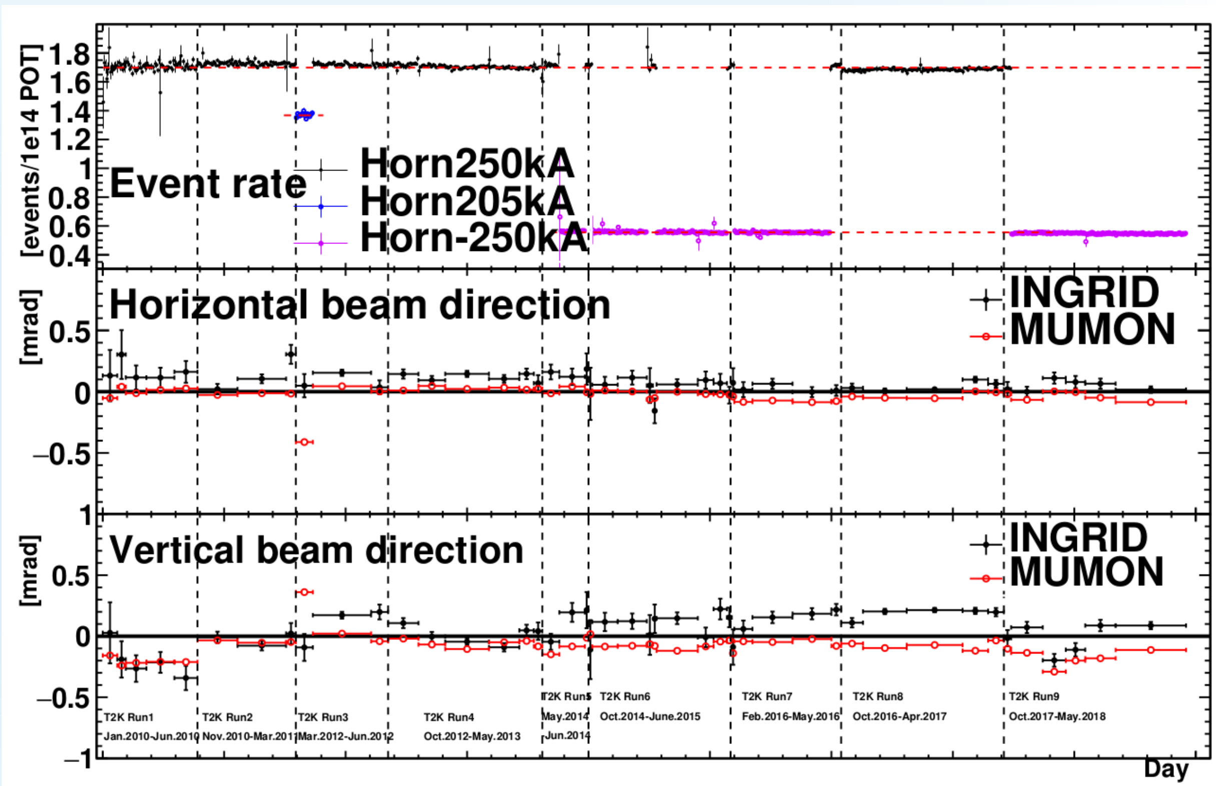
Neutrino charged current interactions at T2K

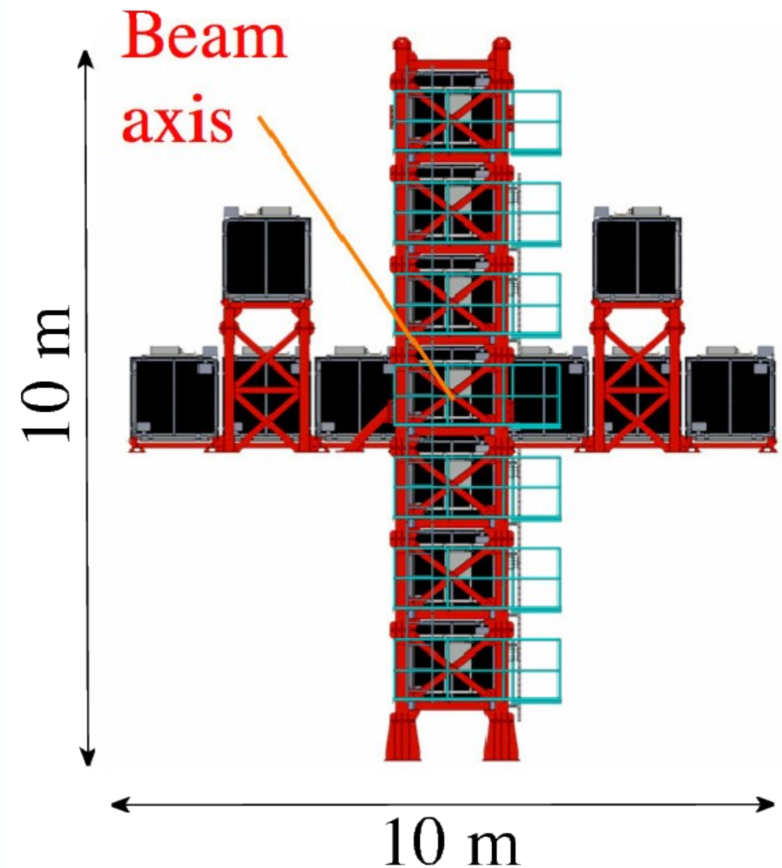




- Off-axis strategy enhances oscillation effect and CCQE interactions.
- Around T2K beam peak (~600 MeV), mostly CCQE and resonant reactions occur.
- δOA~1mrad (0.057°) → δE/E ~2% at far detector

On-axis near detector: INGRID





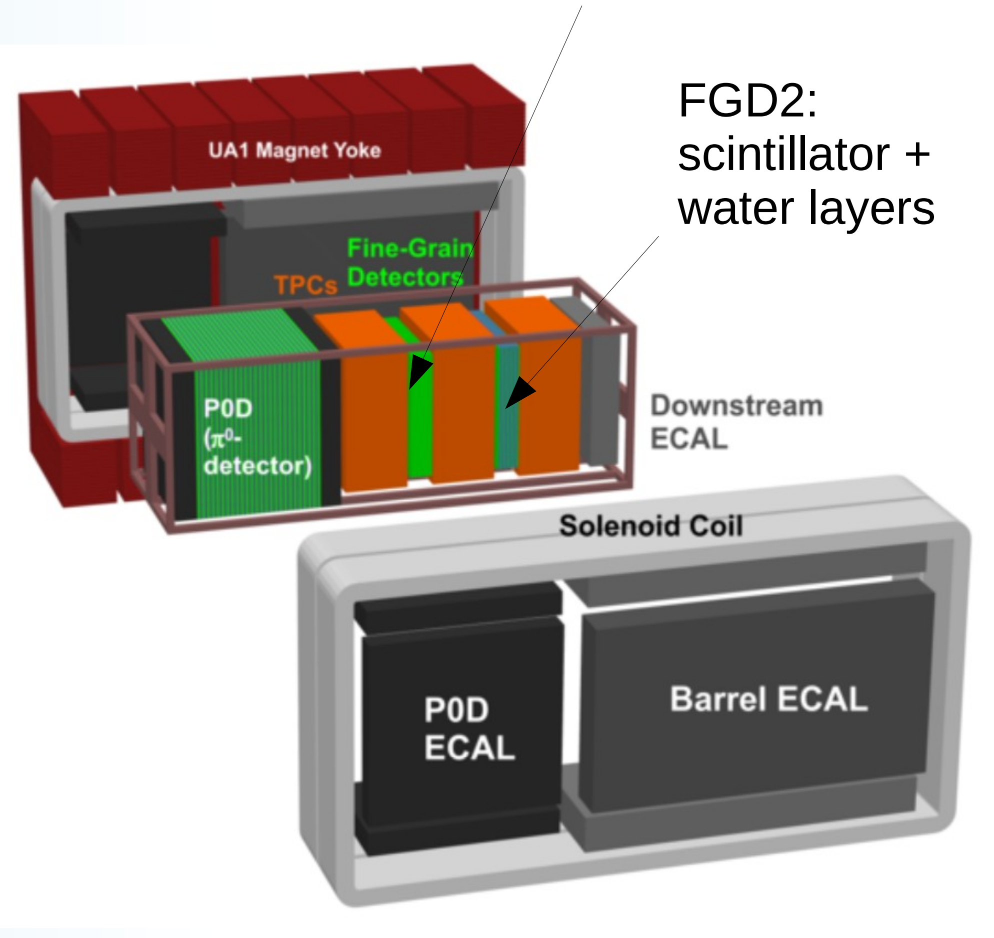
- Cross-shaped detector composed of 16 Fe/scintillator and 1 scintillator modules.
- Monitors beam's direction, profile and intensity.

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 measured 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.

FGD1: scintillator layers

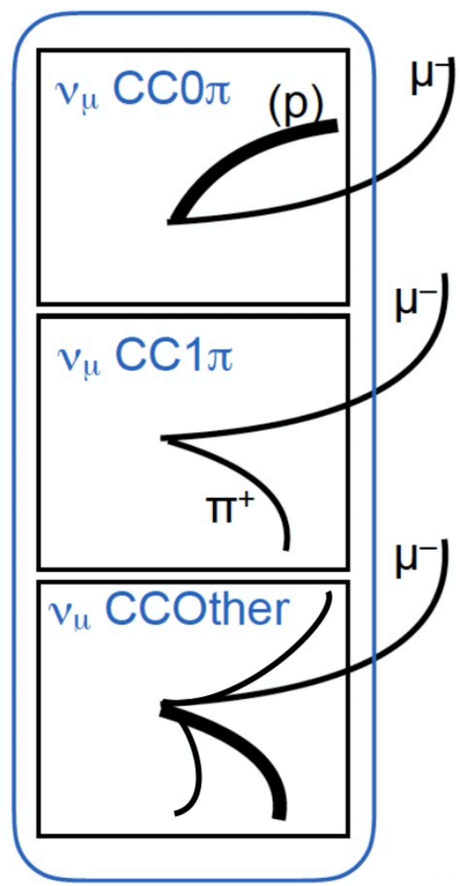
FGD2: scintillator + water layers



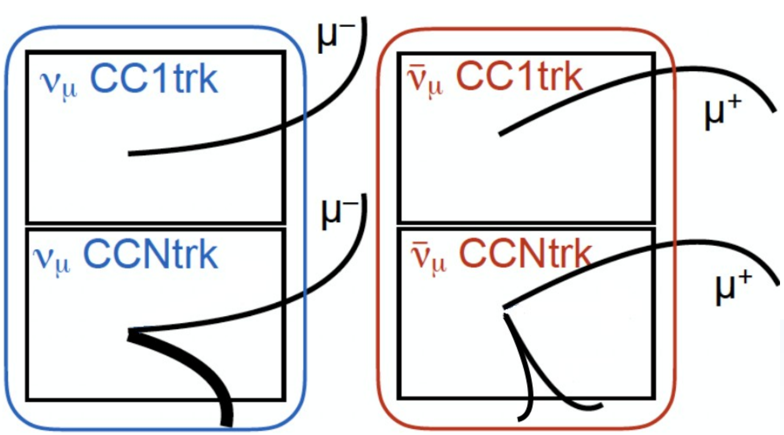
ND280 data fitting

- Several samples of events:
  - For neutrino and antineutrino modes
  - Different reaction types (pion/track multiplicity)
  - C and O target nuclei

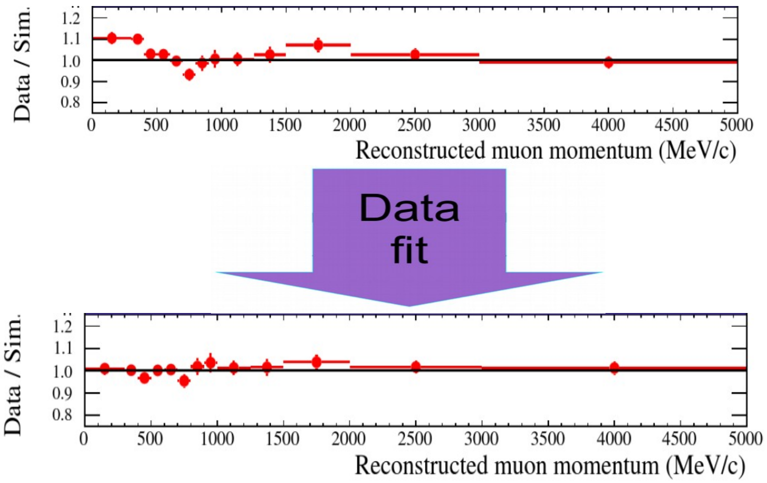
Neutrino mode



Antineutrino mode



Data/MC ratio distribution in ND280 prior and after the data fit.

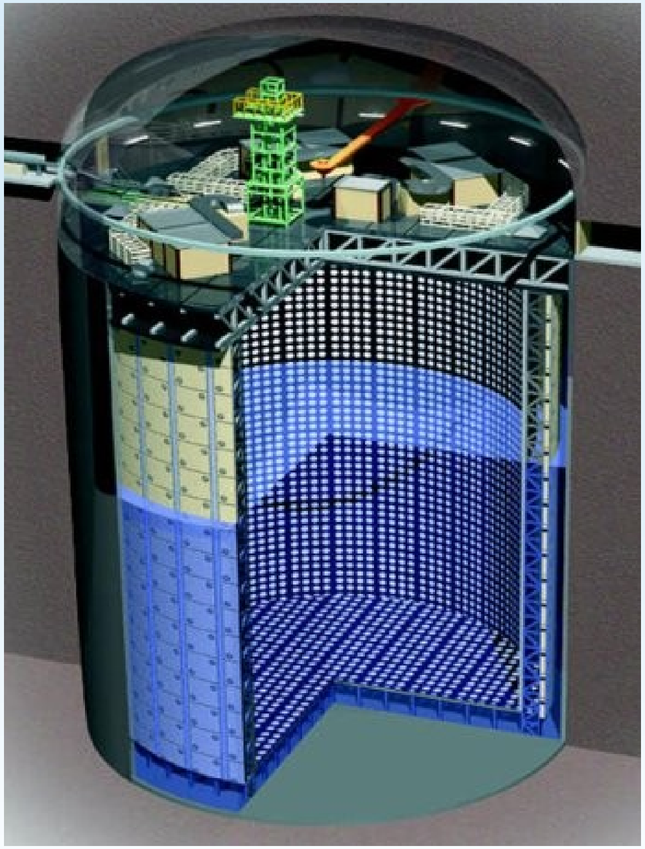


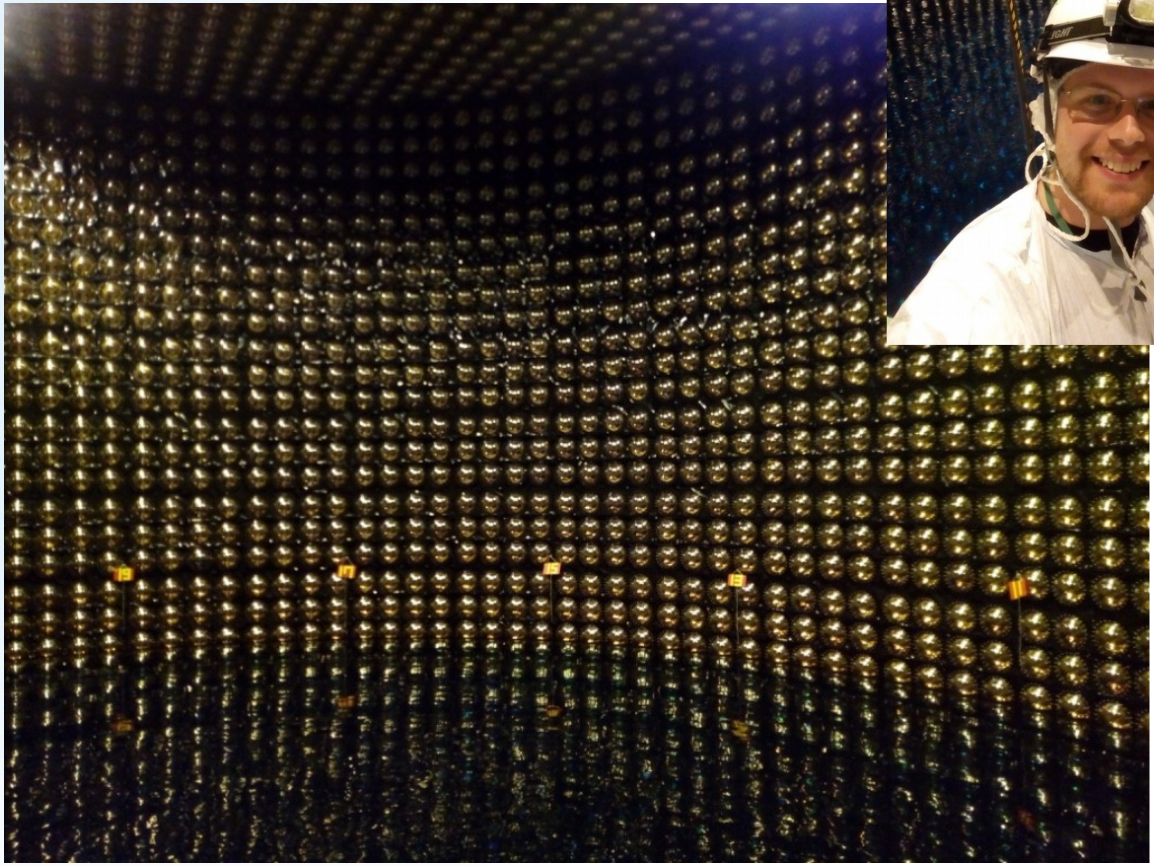
Systematic uncertainty on the predicted SK event rate w/o and with ND280 fit.

	Total syst. error (%)	
Selection	Pre	Post
ν-mode		
1-ring-μ	15	5
1-ring-e	17	9
1-ring-e + 1π^+	22	18
$\bar{\nu}$-mode		
1-ring-μ	13	4
1-ring-e	14	7

Far detector: Super-Kamiokande

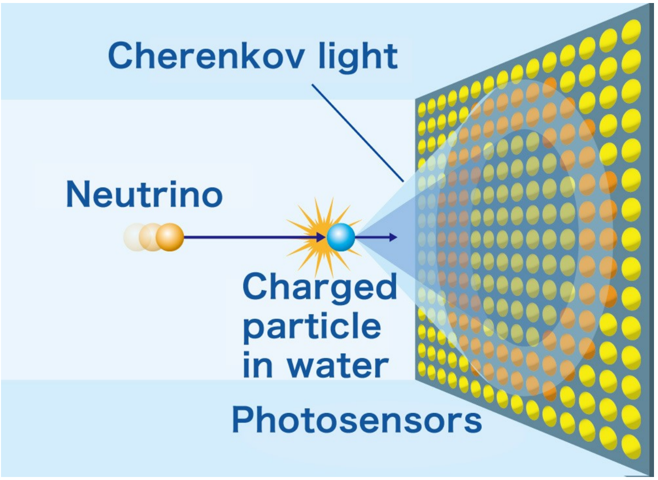
- 50 kton water Cherenkov detector
  - 39 m in diameter, 41 m in height
- Over 10000 PMTs measure the Cherenkov light inside the tank.



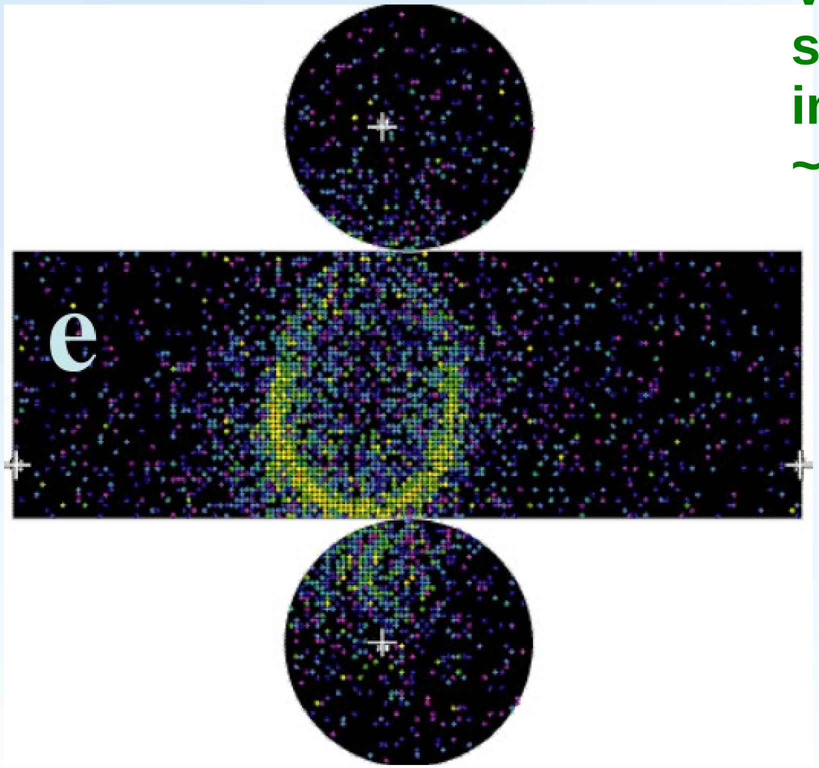


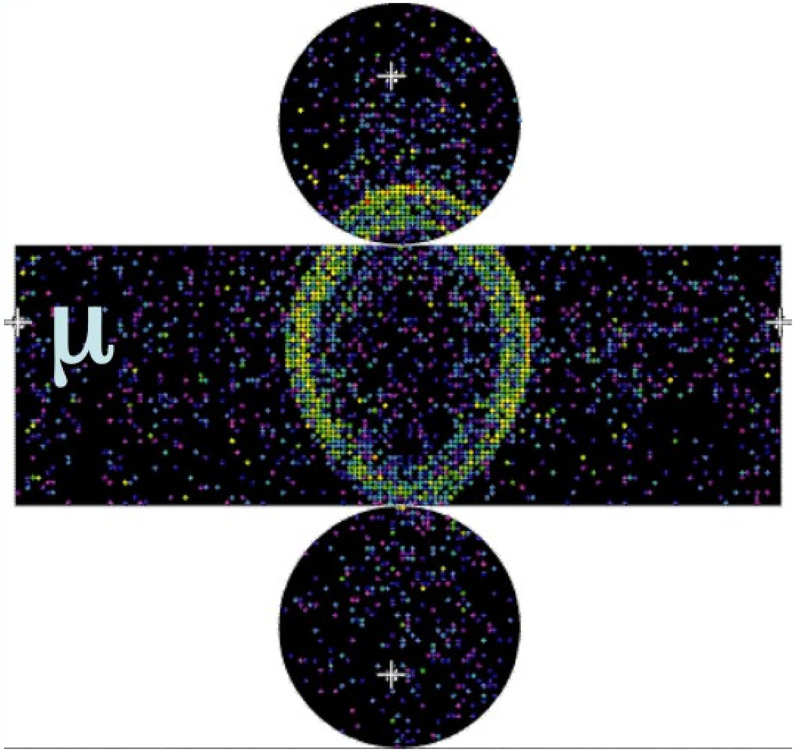
Far detector: Super-Kamiokande

- 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/μ separation in Super-K! ~1% mis-id





Far detector: Super-Kamiokande

- Neutrino beam mode: searching for ν_μ/ν_e CCQE (1-ring-μ/e)

$$\nu_\mu + n \rightarrow \mu^- + p,$$
$$\nu_e + n \rightarrow e^- + p,$$

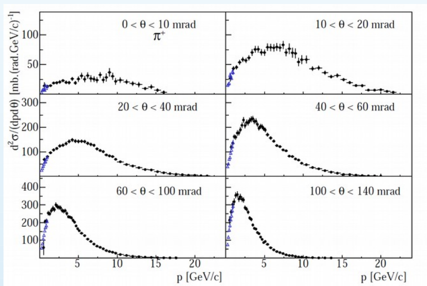
- or ν_e appearance with single pion production (1-ring-e + 1π^+).

$$\nu_e + p \rightarrow e^- + \pi^+ + p \qquad \nu_e + n \rightarrow e^- + \pi^+ + n$$

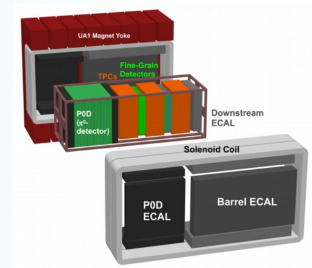
- Antineutrino beam mode: searching for $\bar{\nu}_\mu/\bar{\nu}_e$ CCQE (1-ring-μ/e).

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n,$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Analysis strategy

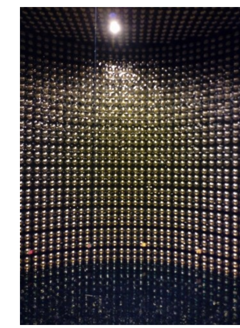


NA61/SHINE external data



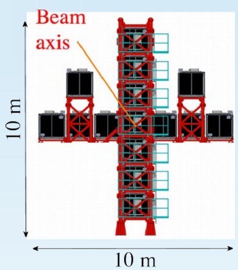
ND280 detector model

ND280 data



Super-K detector model

INGRID & Beam monitor data



Neutrino flux model

ND280 Fit
systematics
~2x smaller

Super-K data

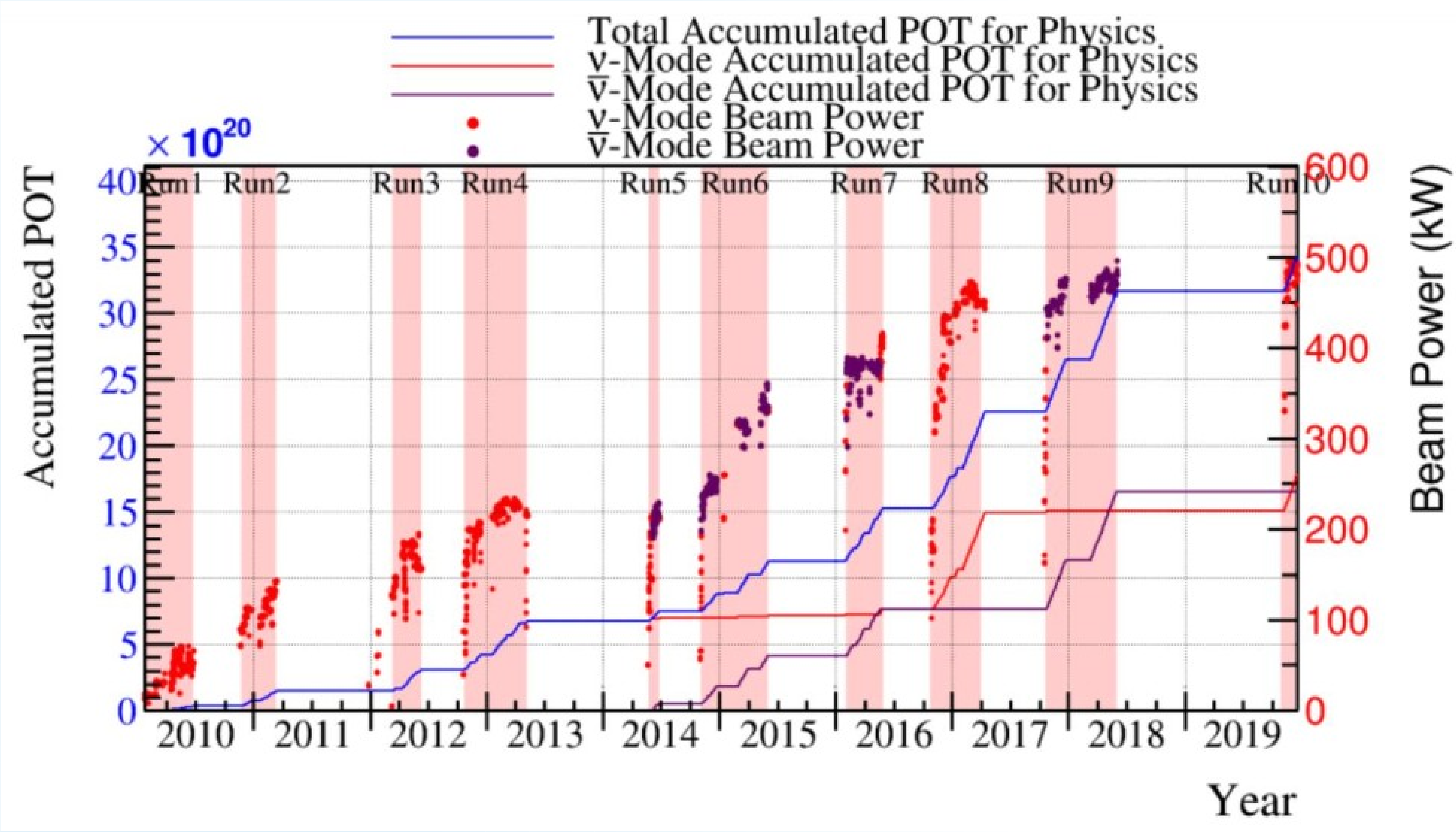
Cross-section model

External cross-section data

Oscillation Fit

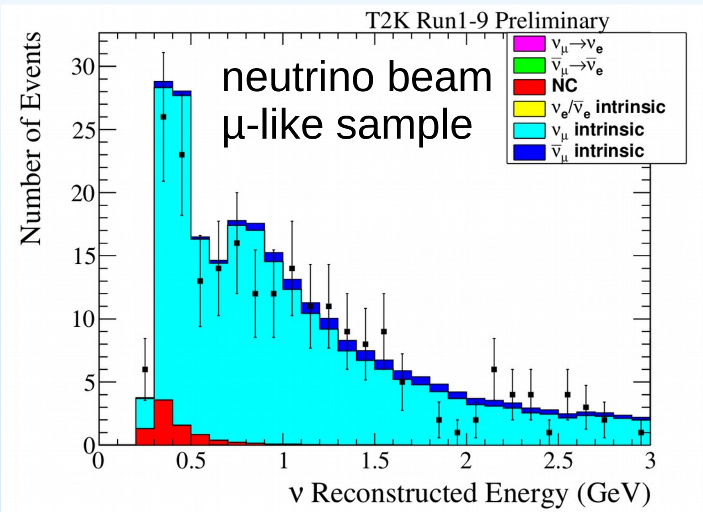
Oscillation parameters

T2K collected statistics

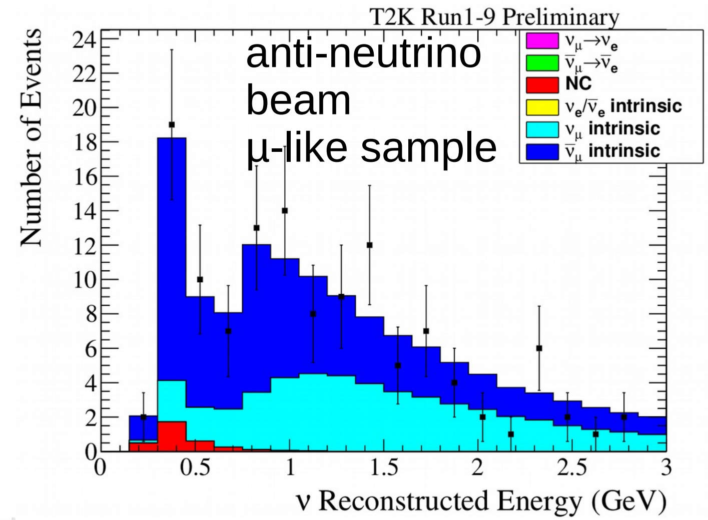


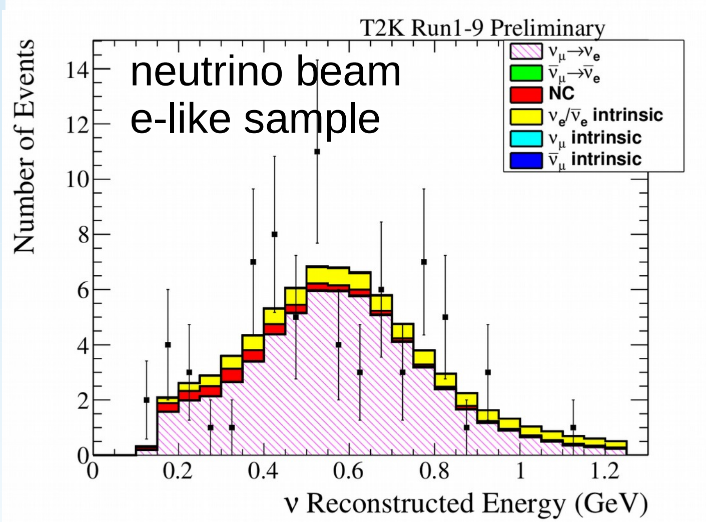
- 3.43×10^{21} Protons On Target (POT) collected so far.
  - 1.78×10^{21} for neutrino, 1.65×10^{21} for anti-neutrino beam mode.
- Oscillation results based on 3.13×10^{21} POT.
  - 1.49×10^{21} for neutrino, 1.63×10^{21} for anti-neutrino beam mode.

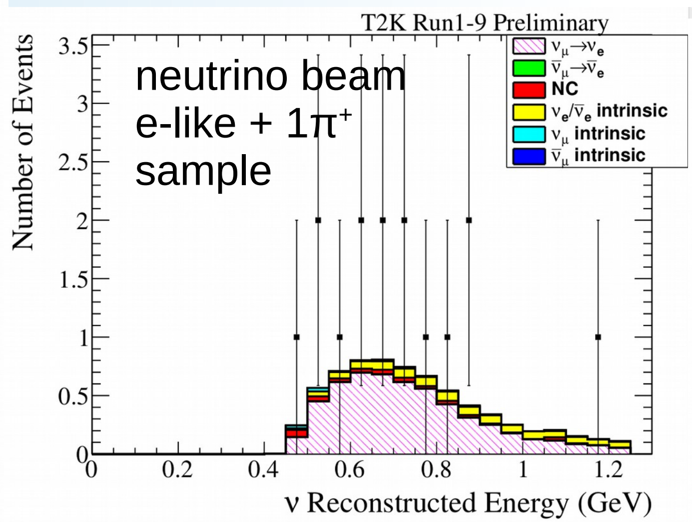
Super-K fit to data

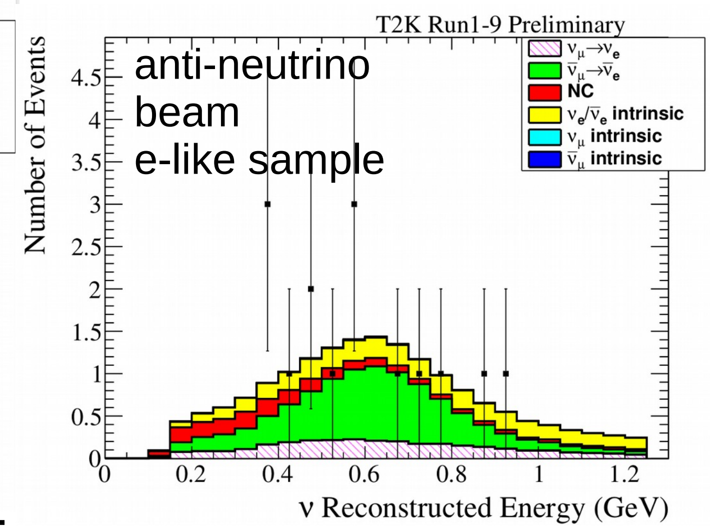


- Fit simultaneously 5 samples.
- Oscillation and systematic parameters are shared between them.









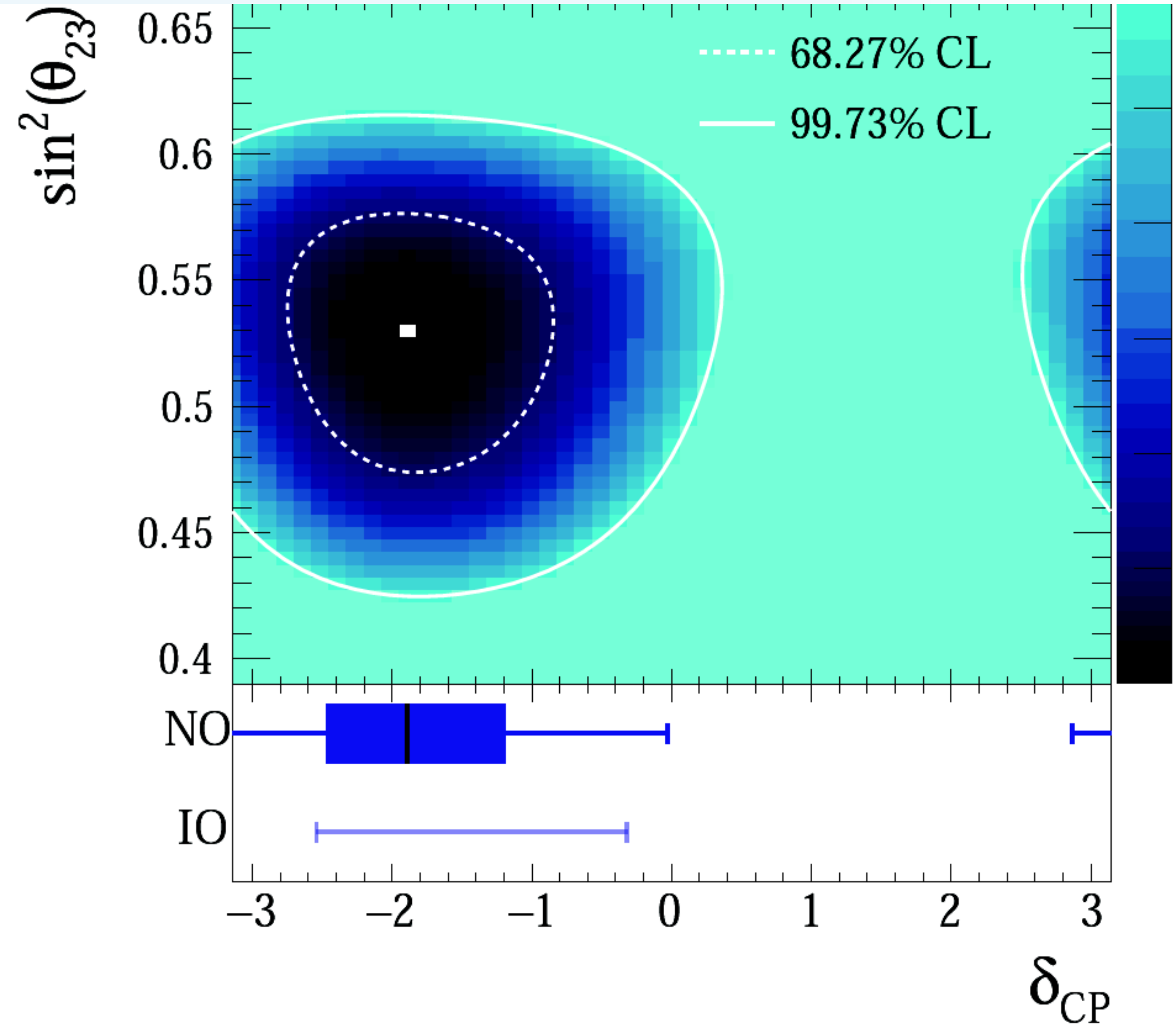
For the MC distributions above:

Normal Hierarchy, $\delta = -\pi/2$, $\sin^2\Theta_{23} = 0.528$, $\sin^2\Theta_{13} = 0.0212$

Super-K predicted/observed events

Sample	Predicted				Observed	Systematic uncertainty for prediction
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$		
ν mode μ-like	272.4	272.0	272.4	272.8	243	5.1%
$\bar{\nu}$ mode μ-like	139.5	139.2	139.5	139.9	140	4.5%
ν mode e-like	74.4	62.2	50.6	62.7	75	8.8%
$\bar{\nu}$ mode e-like	17.1	19.4	21.7	19.3	15	7.1%
ν mode e-like + $1\pi^+$	7.0	6.1	4.9	5.9	15	18.4%

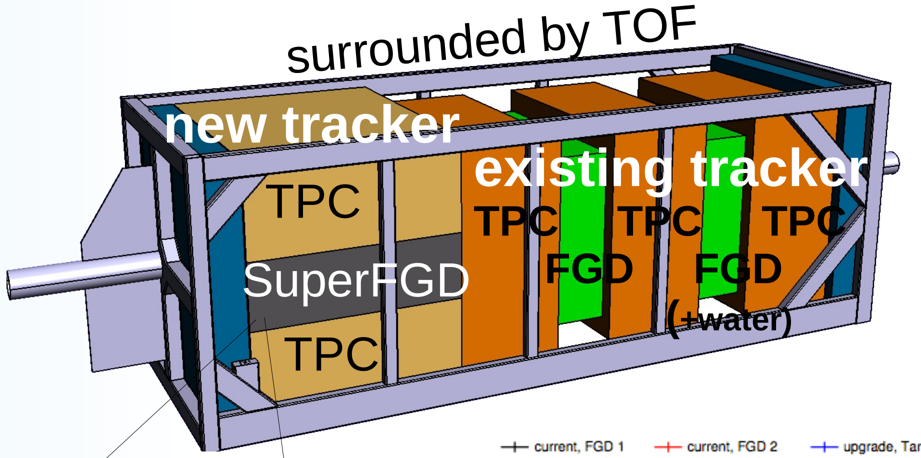
Results: $\sin^2(\Theta_{23})$ vs δ_{CP}

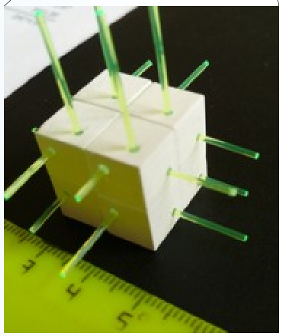


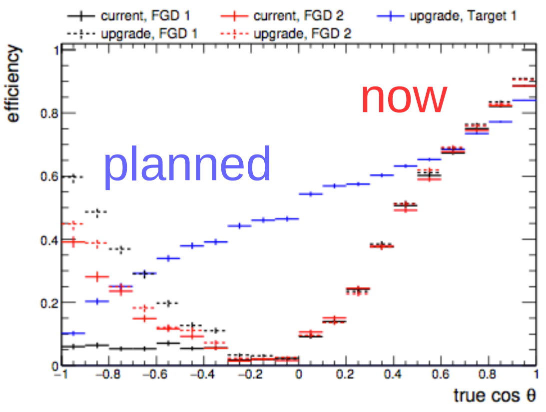
- CP-conserving values excluded at 2σ level
  - $\delta_{CP} = 0$ excluded at 3σ level
- Normal Hierarchy preferred (89%)
  - Best fit: $\delta_{CP} = -1.885$ (-0.6π) for NH

T2K's future

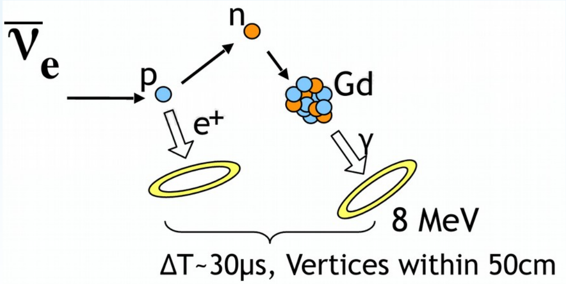
- Upgrade of ND280 for T2K Phase-II (2021-2026)
  - SuperFGD
  - High angle TPCs
  - Reduction of systematic errors to ~4%
- Upgrade of Super-K
  - Dissolving gadolinium
  - Enhance neutron detection capability
  - Improve antineutrino detection



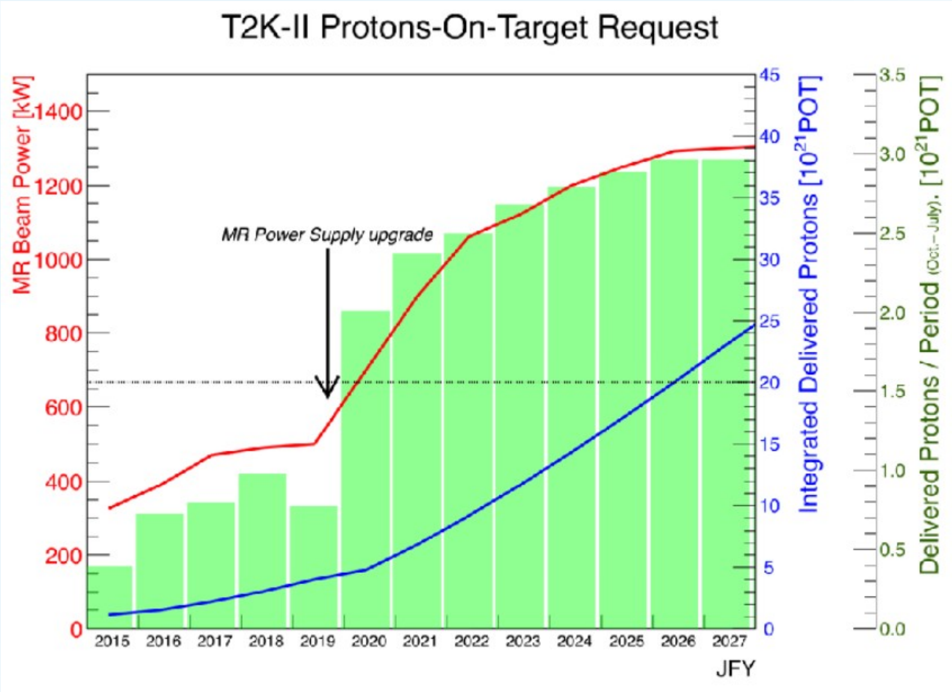


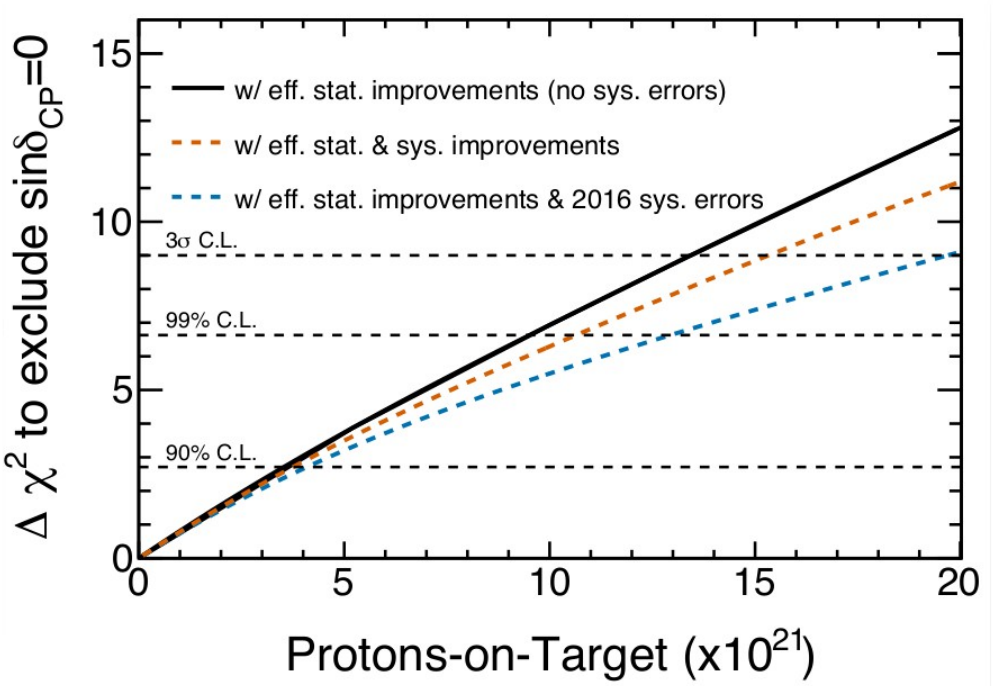


angular efficiency



T2K's future

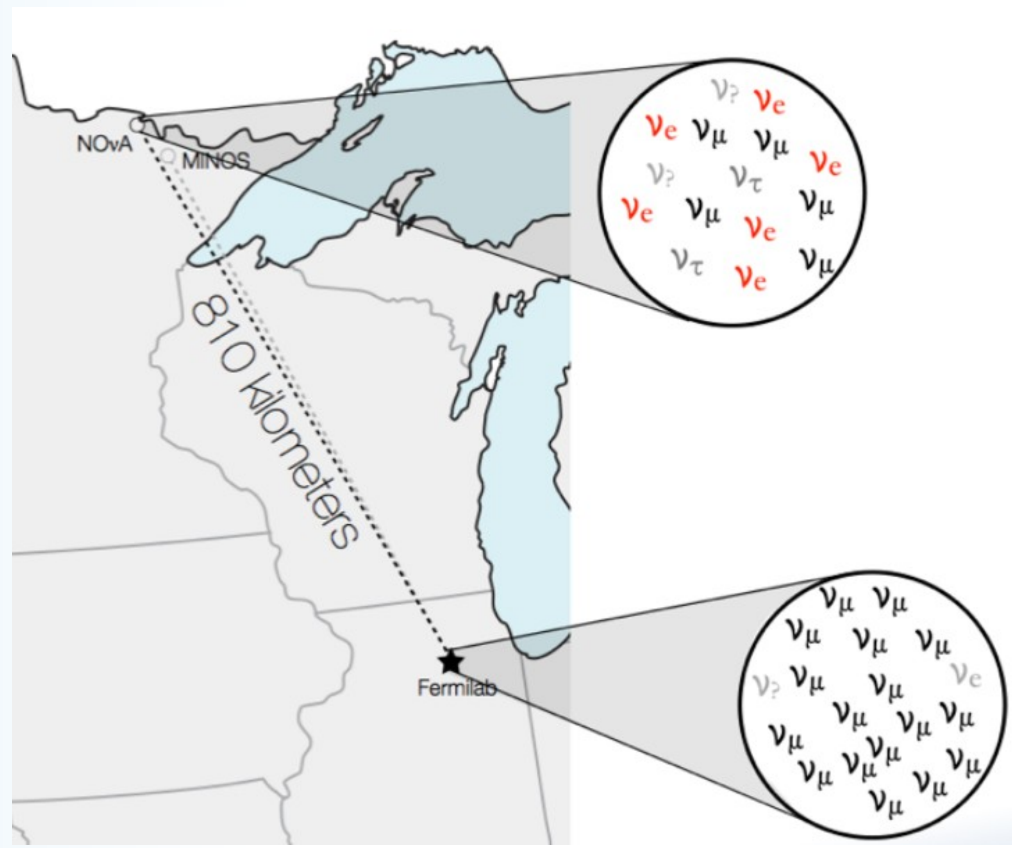




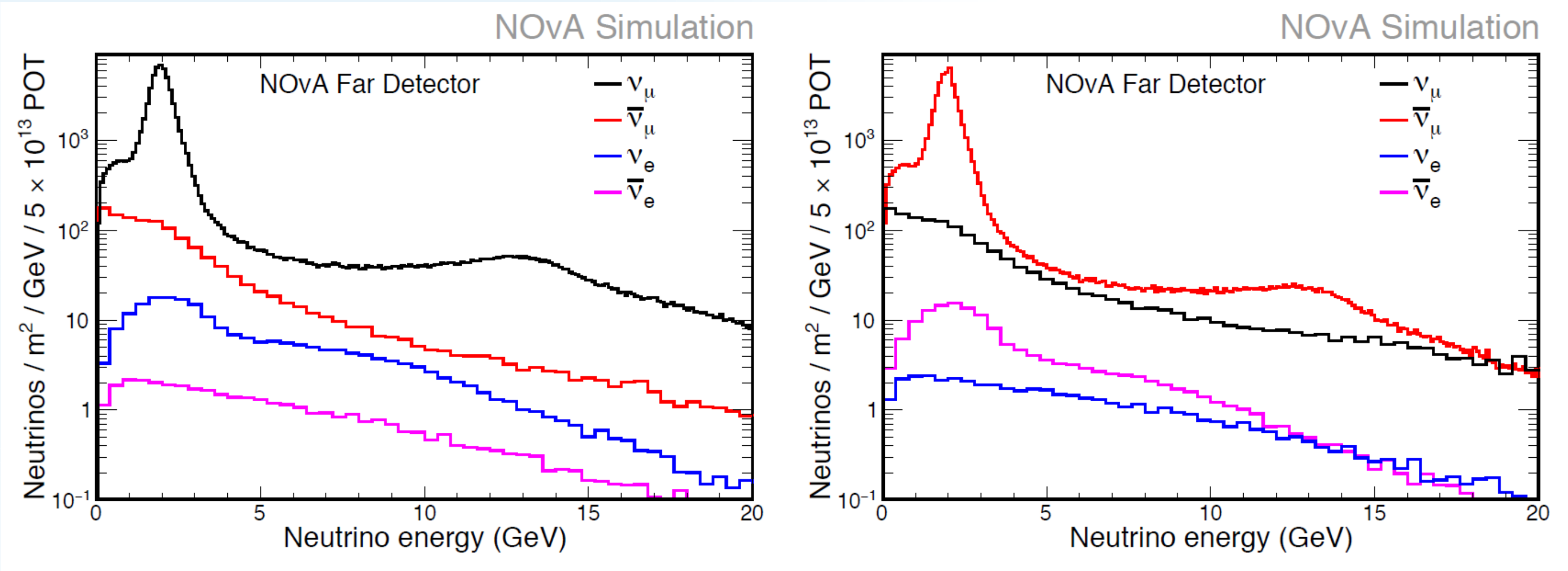
- Plan to double Collected statistics till the 2021 (up to 7.8 E21 POT).
- Plan to improve the analysis:
  - New samples
  - Joint fit beam + atmospheric neutrinos
- Aiming for 20 E21 POT in 2026 (T2K Phase-II)

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 and Far detector are functionally identical and situated 810 km apart, both 14 mrad off-axis.

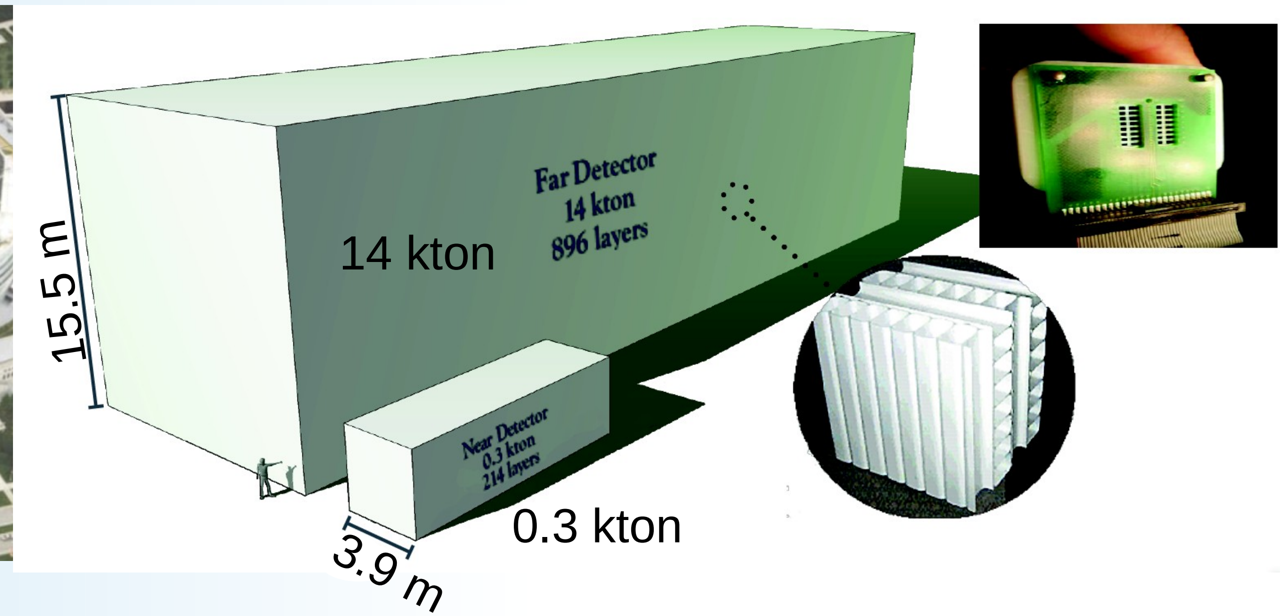


NuMI beam



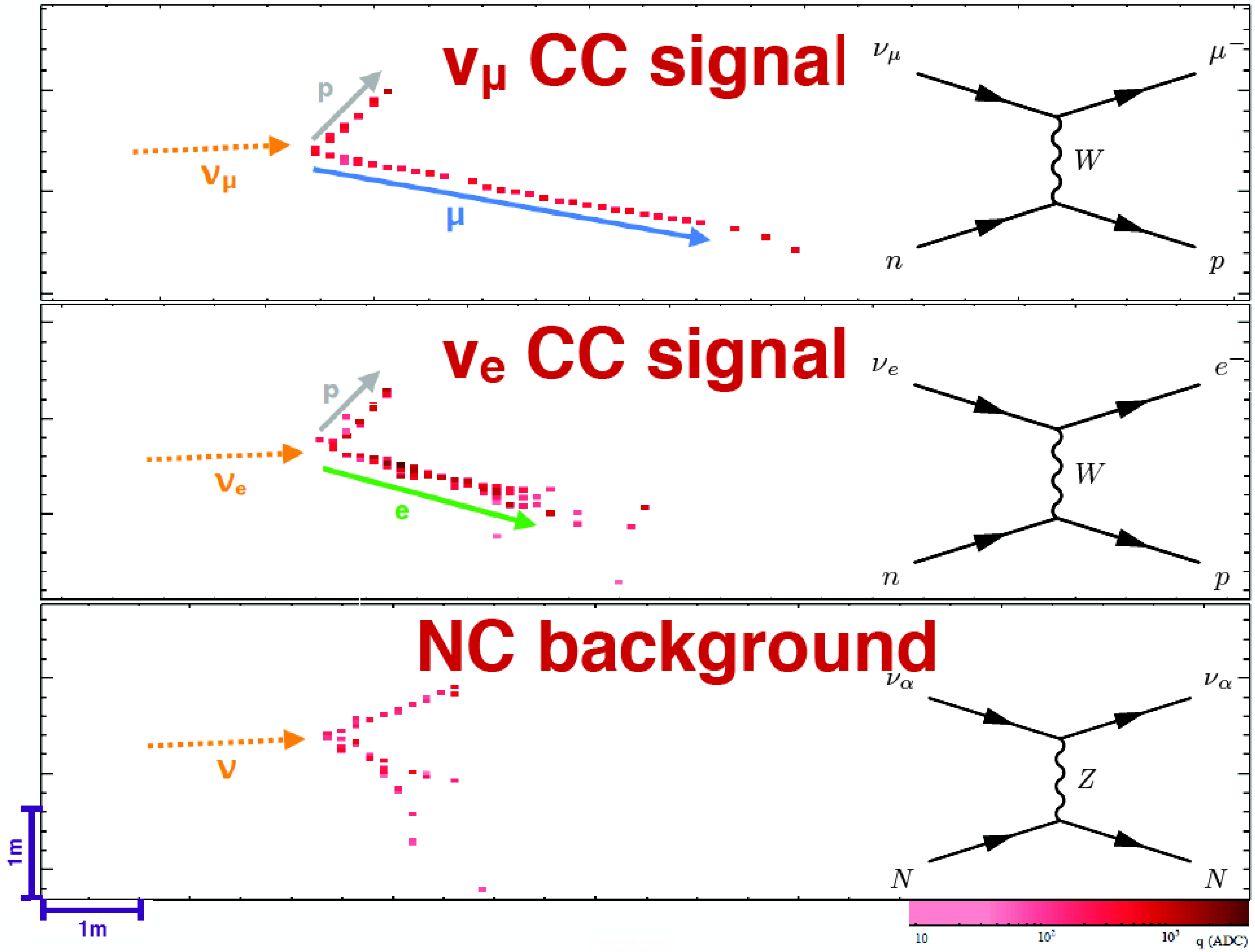
- Fermilab's Neutrinos at the Main Injector (NuMI) beam.
- Beam may be used in neutrino or antineutrino mode.

NOvA detectors



- Both detectors are based on the same detection technique.
- Layers of plastic cells with alternating horizontal and vertical orientation with liquid scintillator inside.

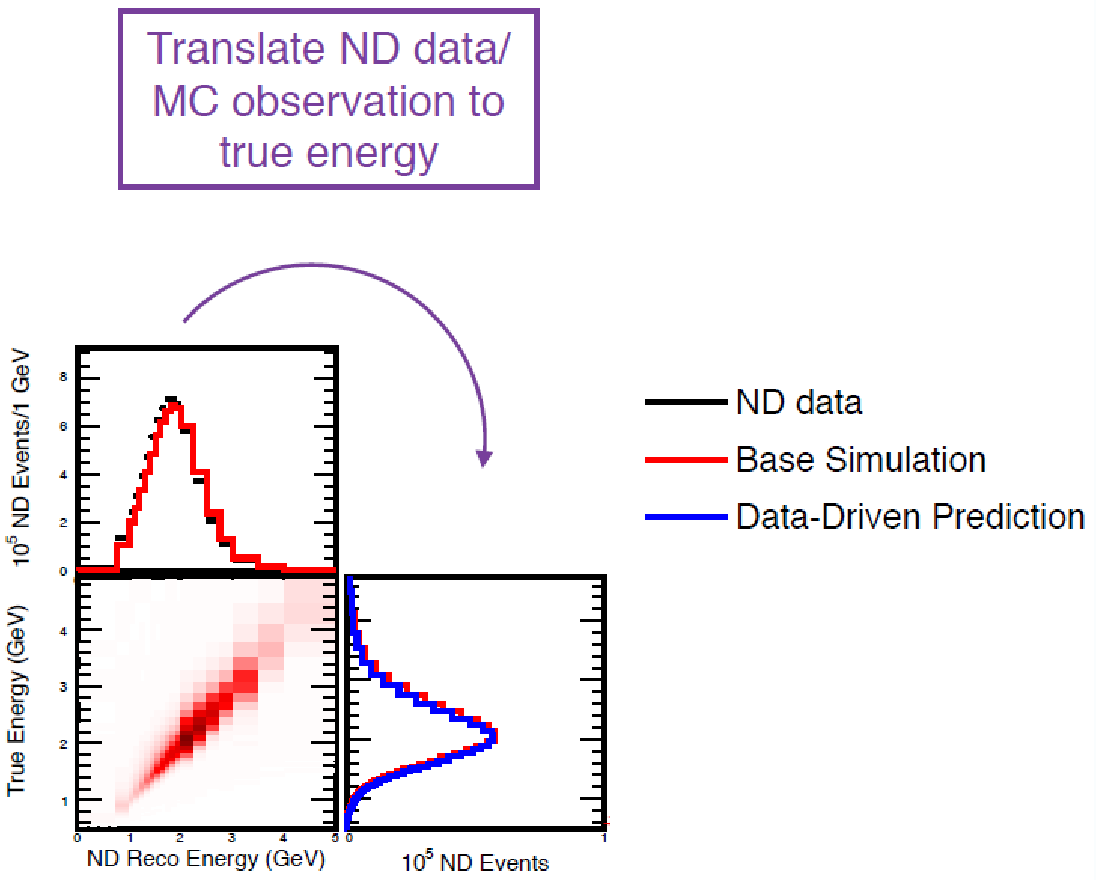
NOvA event topologies



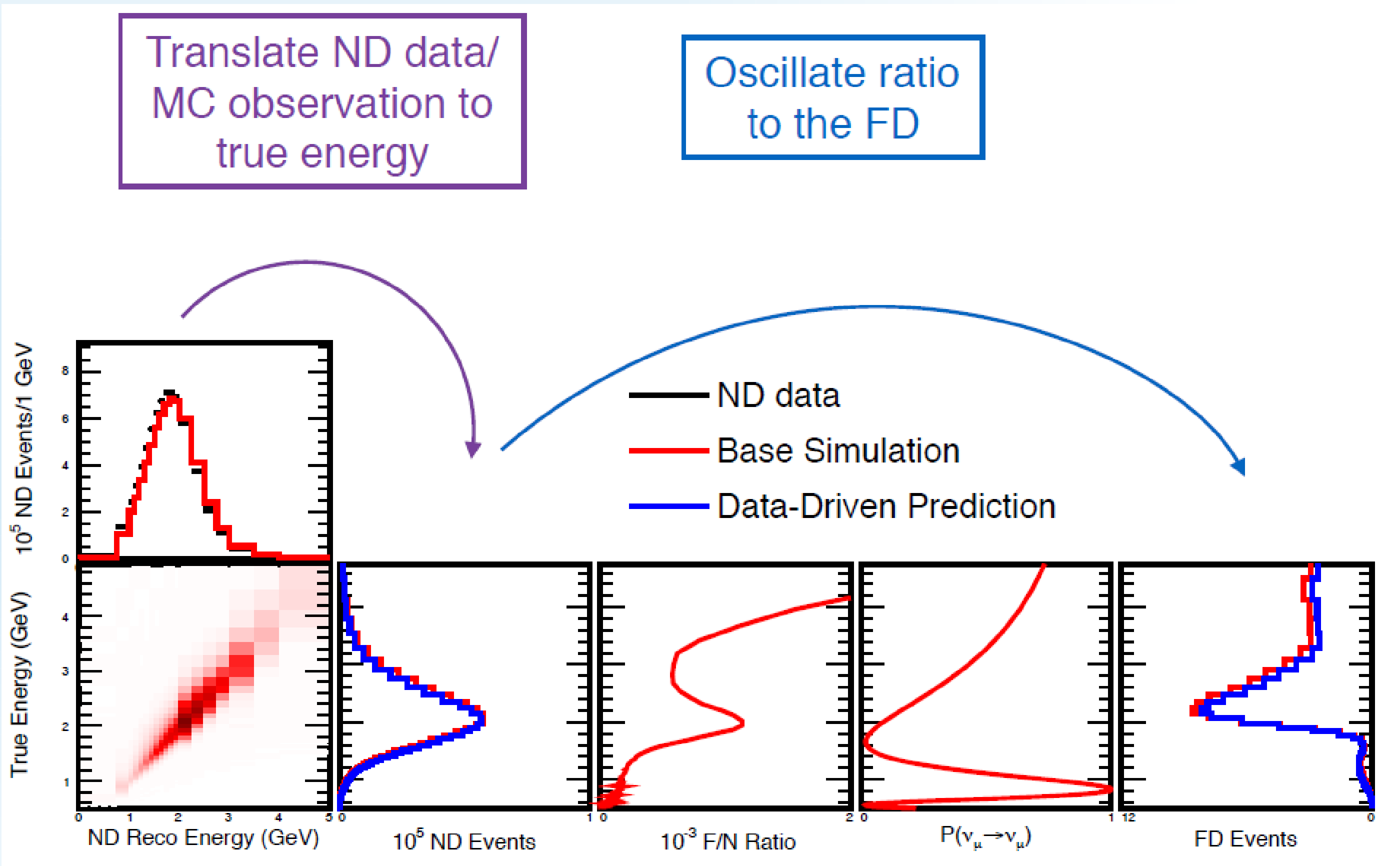
L. Cremonesi (UCL)

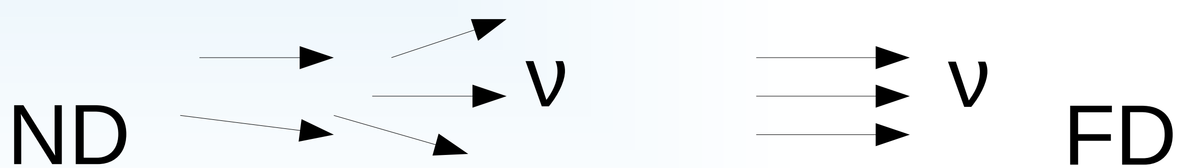
La Thuile 2019

Extrapolation to Far Detector

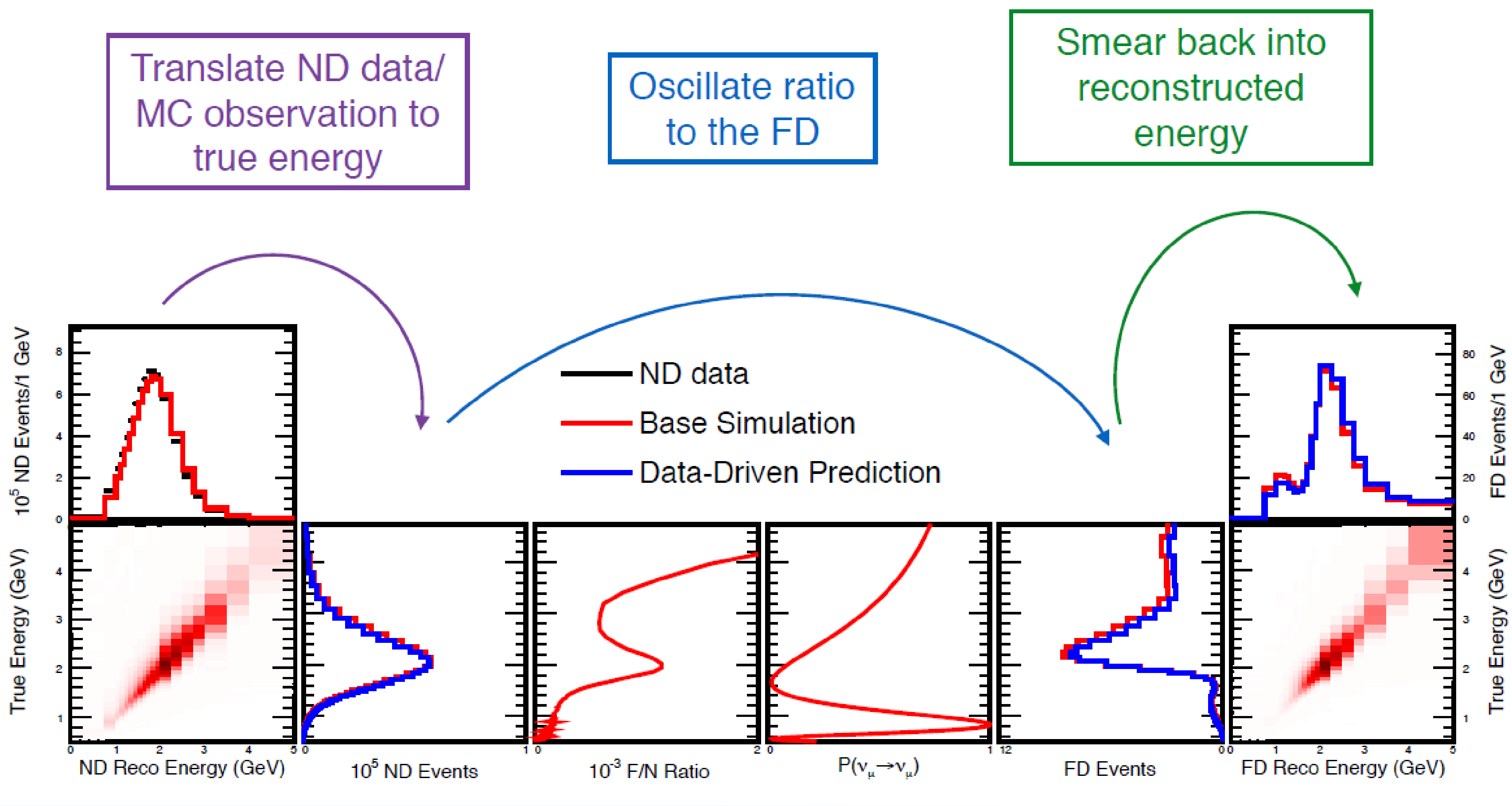


Extrapolation to Far Detector

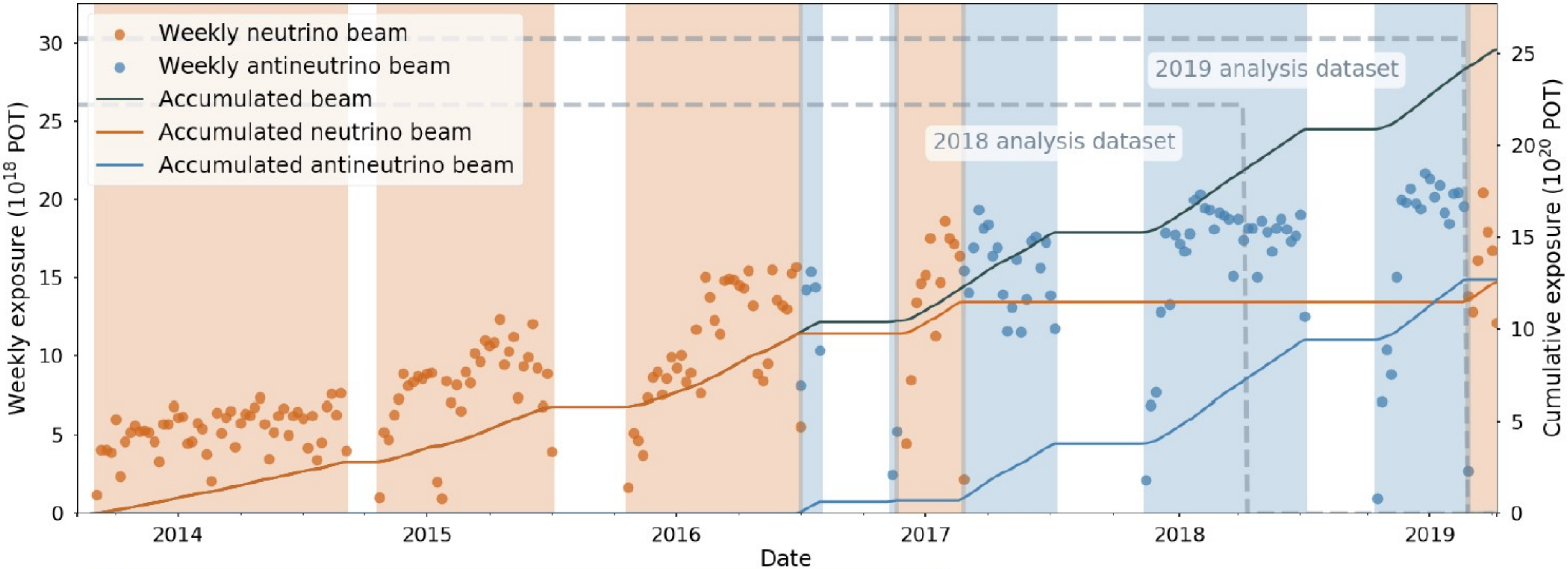




Extrapolation to Far Detector



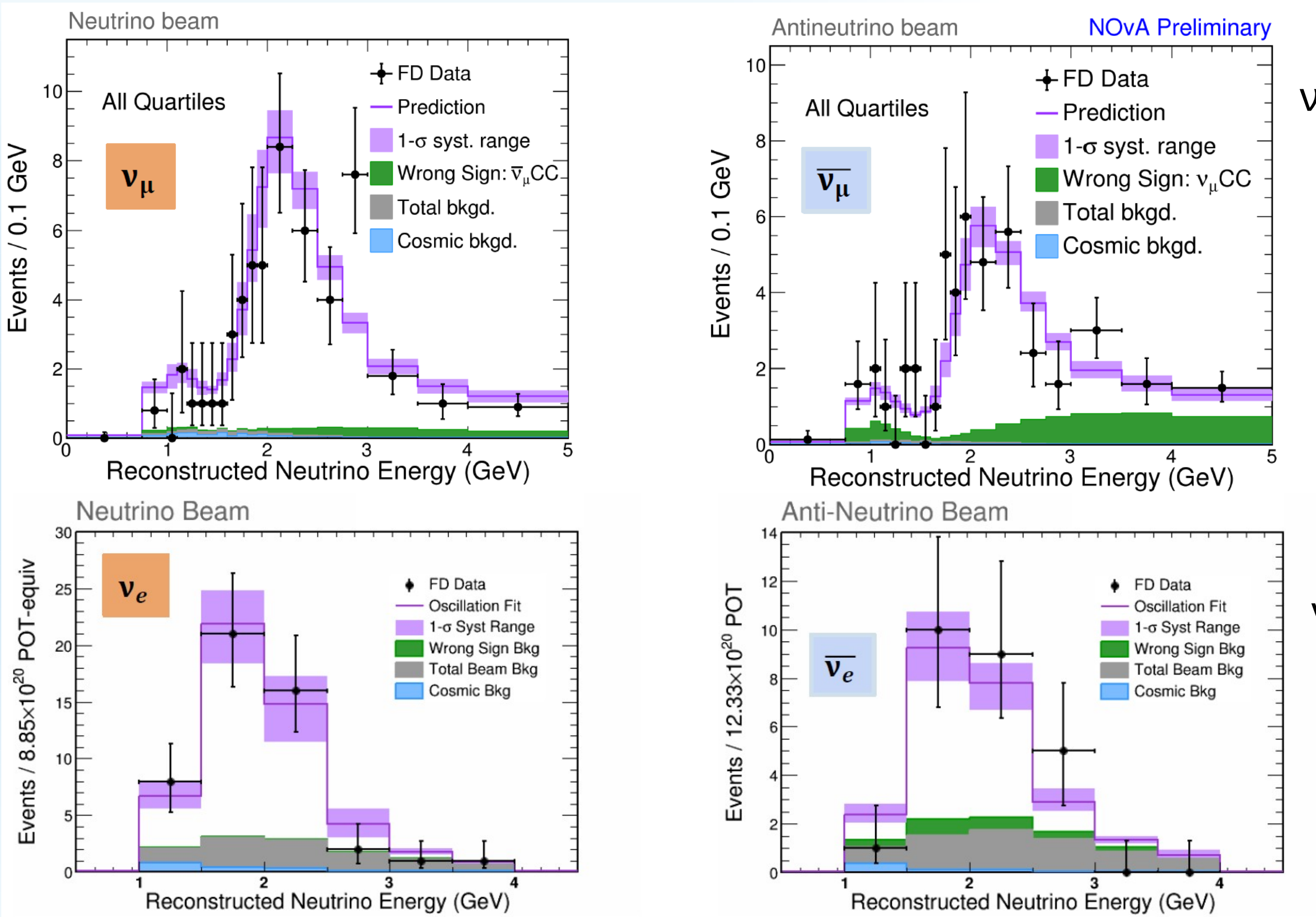
NOvA collected statistics



8.85x10^{20} POT neutrino beam

12.33x10^{20} POT antineutrino beam

Far detector fit to data

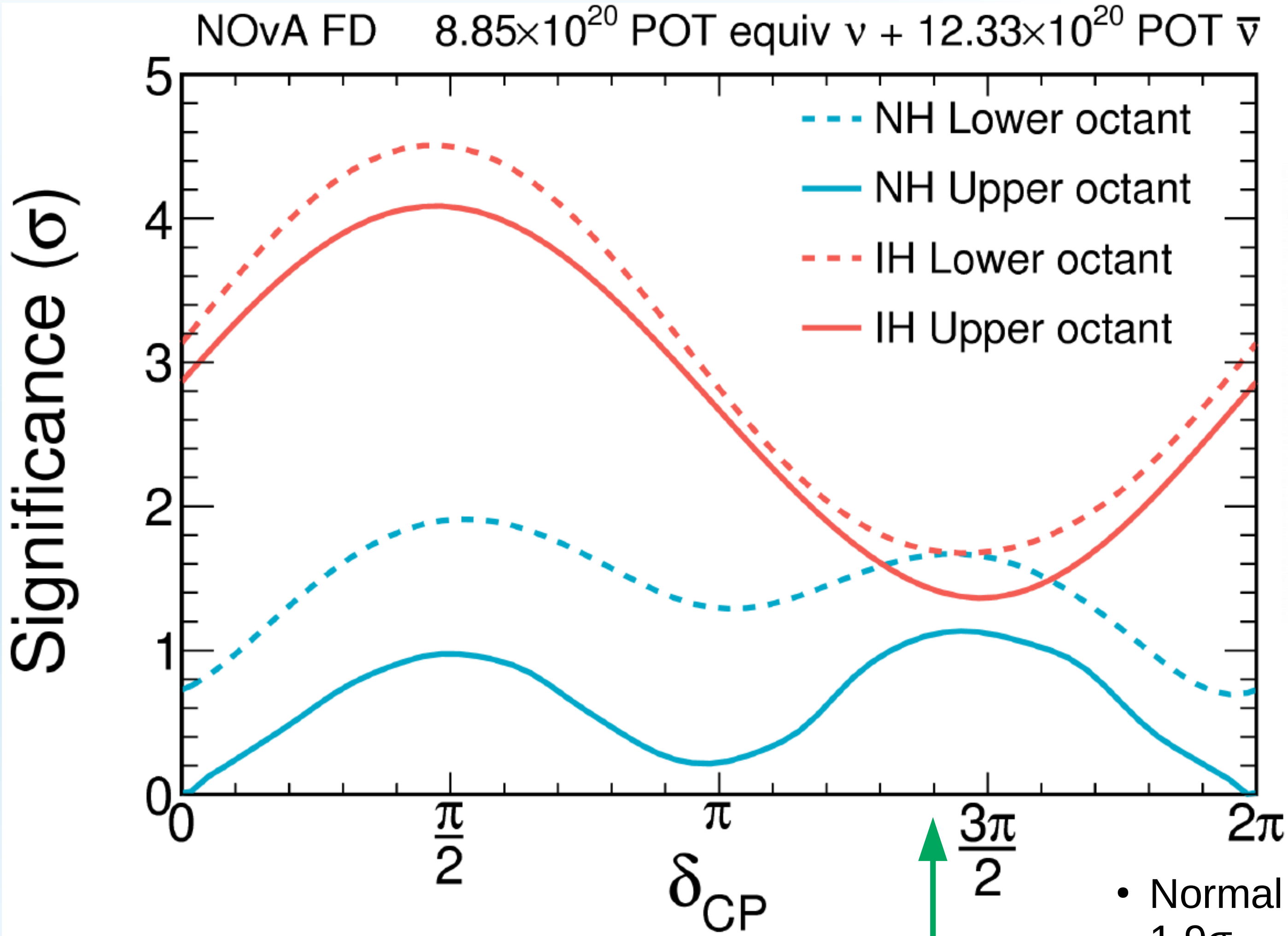


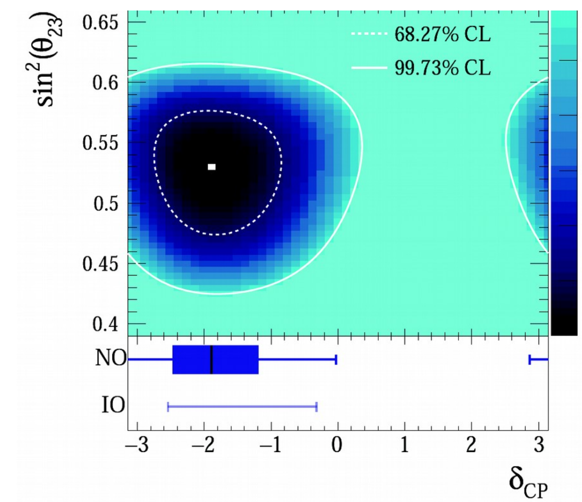
ν_μ / $\bar{\nu}_\mu$ disappearance

ν_e / $\bar{\nu}_e$ appearance

4.4 σ evidence of electron anti-neutrino appearance

Allowed δ_{CP} values



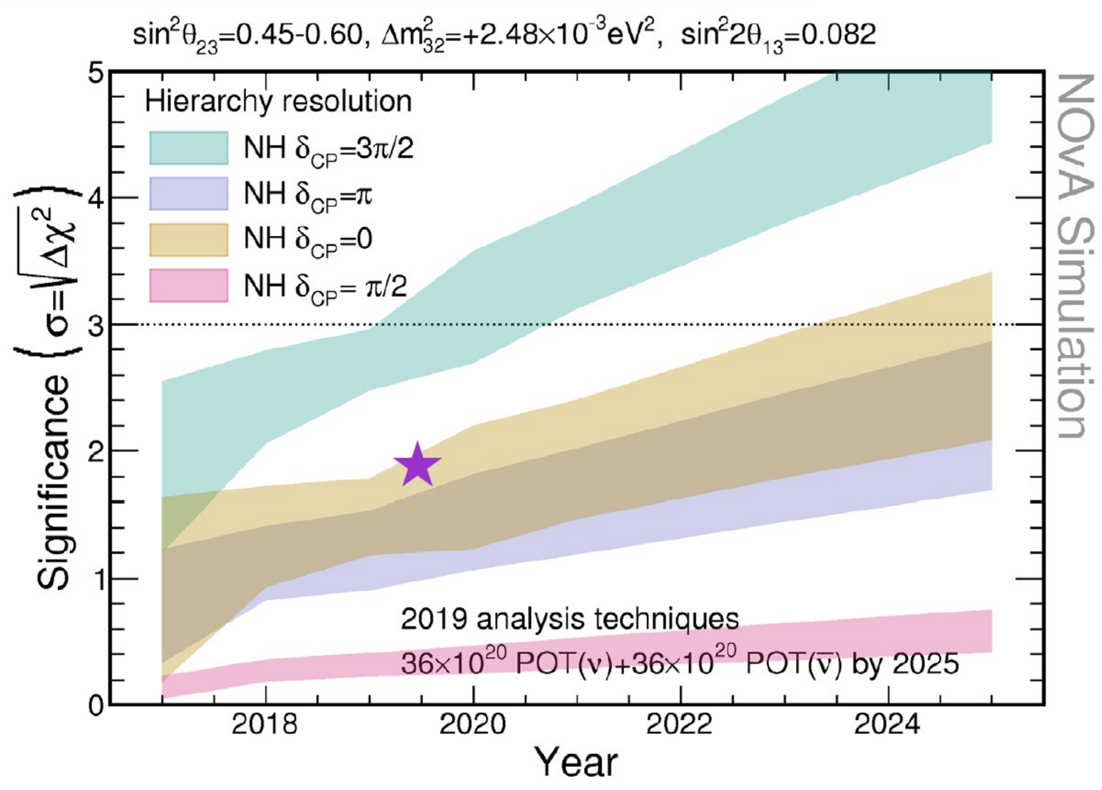


T2K result

T2K best fit for NH

- Normal Hierarchy preferred by 1.9σ
- NOvA best fit:
  - $\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi$
  - All values of δ_{CP} allowed at 1.1σ (NH, UO)

NOvA's future

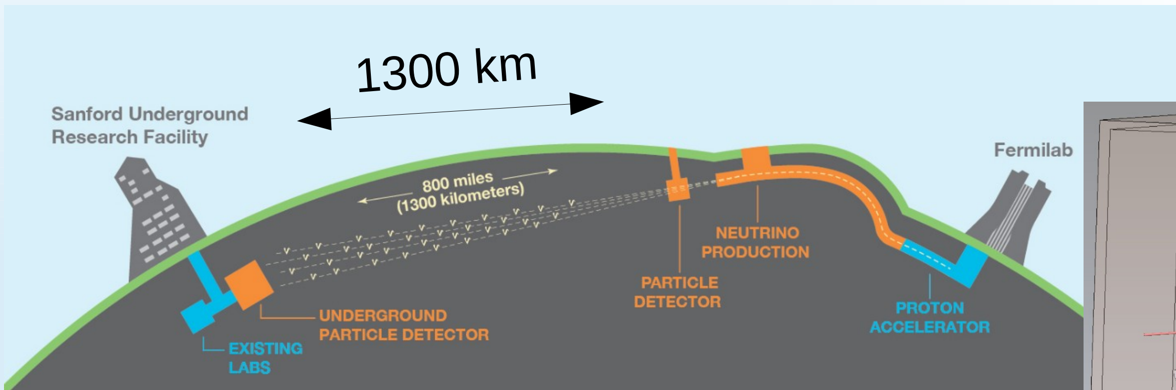


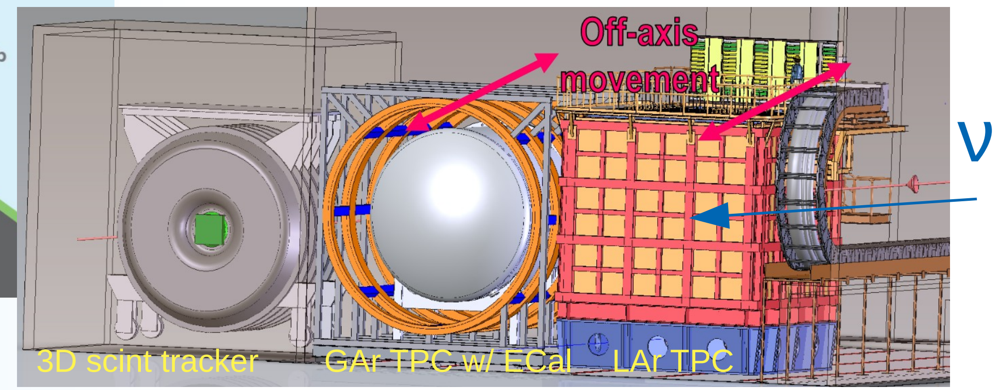
- Running until ~2025
- >3σ sensitivity to mass hierarchy (in case of NH and maximal CP violation) for allowed range of θ_{23} by 2025.
- >2σ sensitivity to CP violation in both hierarchies (in case of maximal CP violation) by 2025.

Outline

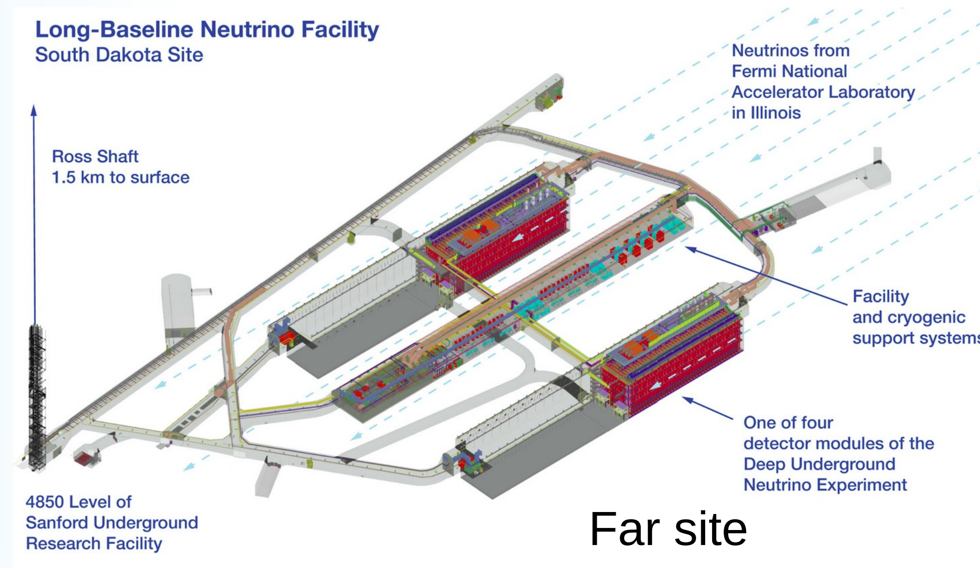
- Introduction: CP violation, neutrino oscillations
- Current leading long-baseline experiments:
  T2K and NOvA
- Future experiments: DUNE and Hyper-Kamiokande
- Summary

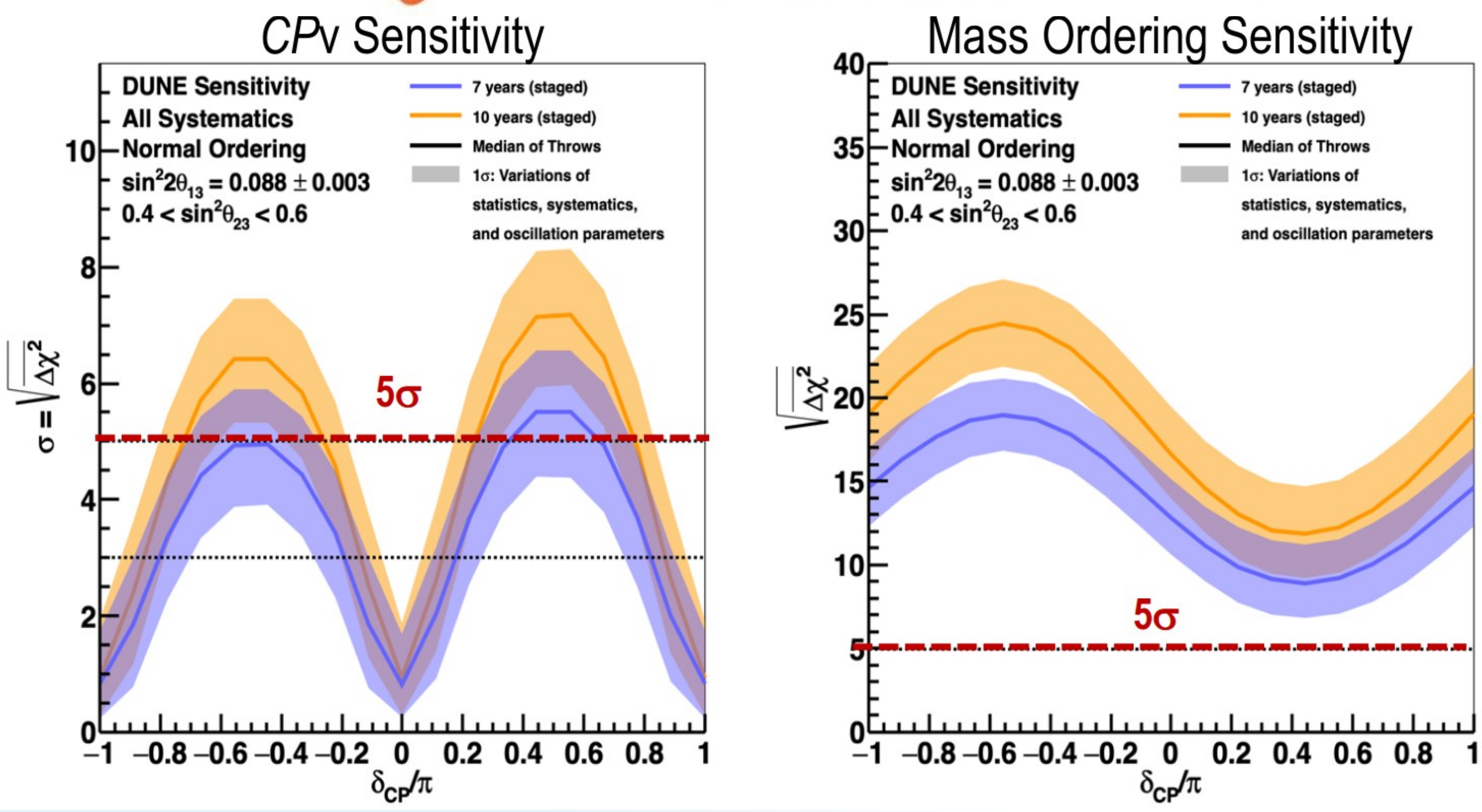
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT





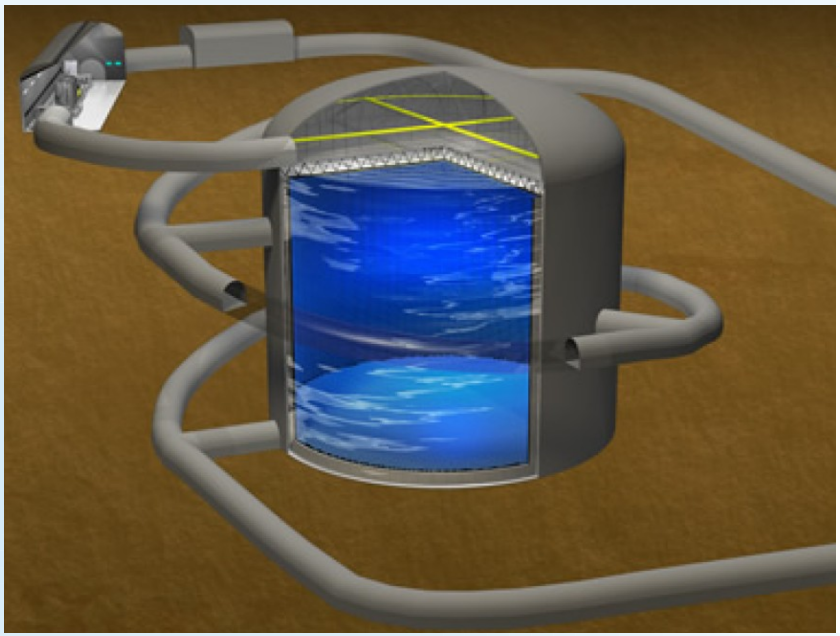
- A high-performance neutrino detector and beamline measurement system a few hundred meters downstream of the neutrino source. On-axis experiment.
  - Unprecedentedly large sample of neutrino interactions.
- A massive liquid argon time-projection chambers located almost a mile underground at the far site.
  - Four 17 000 tons modules.

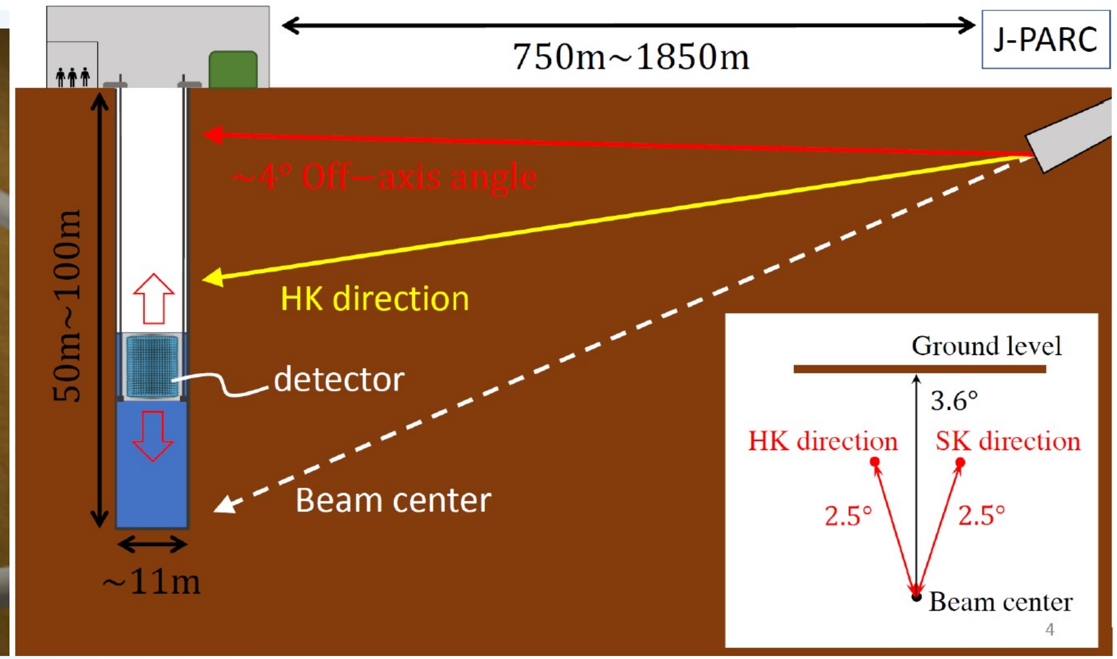




- >5σ sensitivity to CPV over a wide range of δ_{CP}
- Definitive determination of mass hierarchy

Hyper-Kamiokande



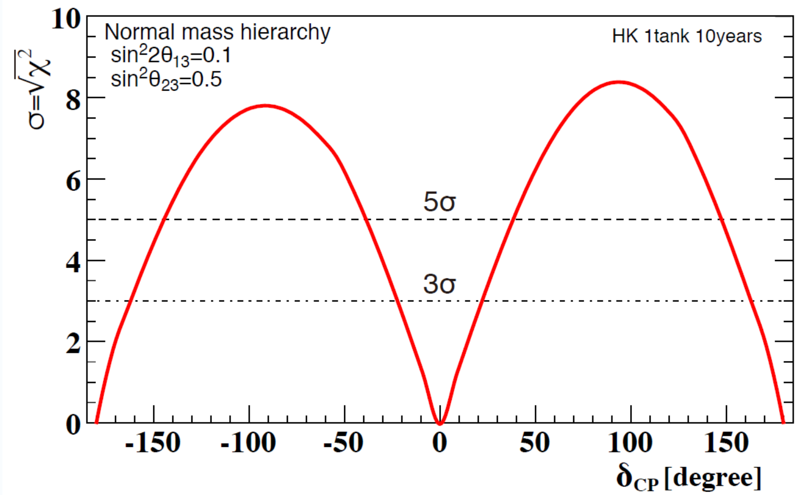


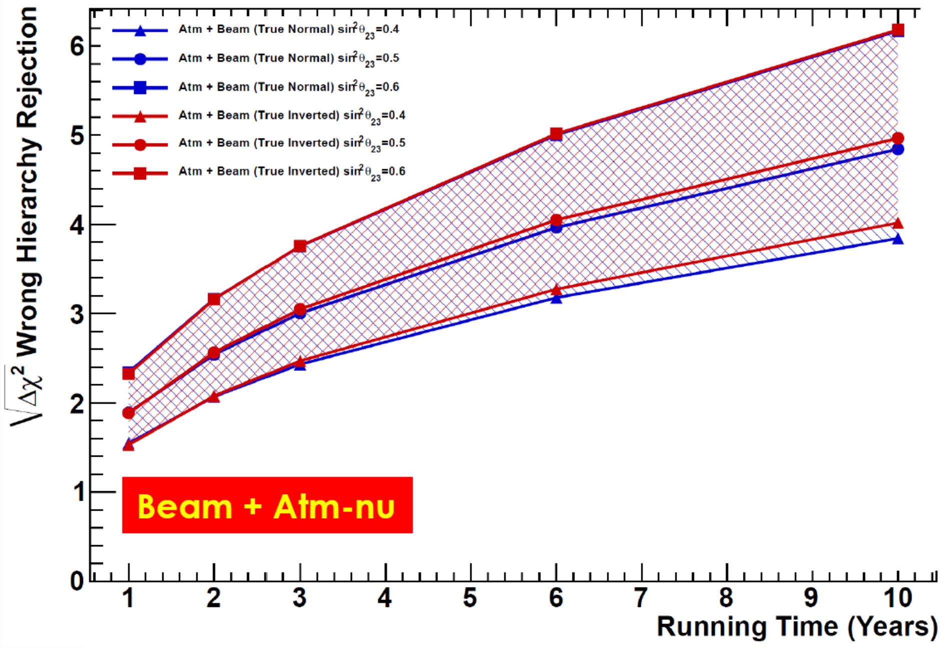
- Next generation underground water Cherenkov detector. It will serve as a far detector of a long baseline experiment (with the same baseline of 295 km) for the upgraded J-PARC beam .
  - 260 kton
  - 74 m in diameter, 60 m in height
  - High sensitivity PMTs

- Intermediate Water Cherenkov Detector ~km from the beam source
- Aims to measure neutrino interactions at many off-axis angles.
- Water in the tank will be enhanced with Gd to tag neutrons.

Hyper-Kamiokande

- Neutrino oscillation physics
  - 5σ sensitivity to CPV for broad range of δ_{CP}
  - ~4σ sensitivity to mass hierarchy by combination of beam and atm-nu
- Both DUNE and Hyper-K will have broad physics program (MeV to TeV scale)
  - Nucleon decay
  - Precision measurement of solar neutrinos
  - Measurement of SN neutrinos



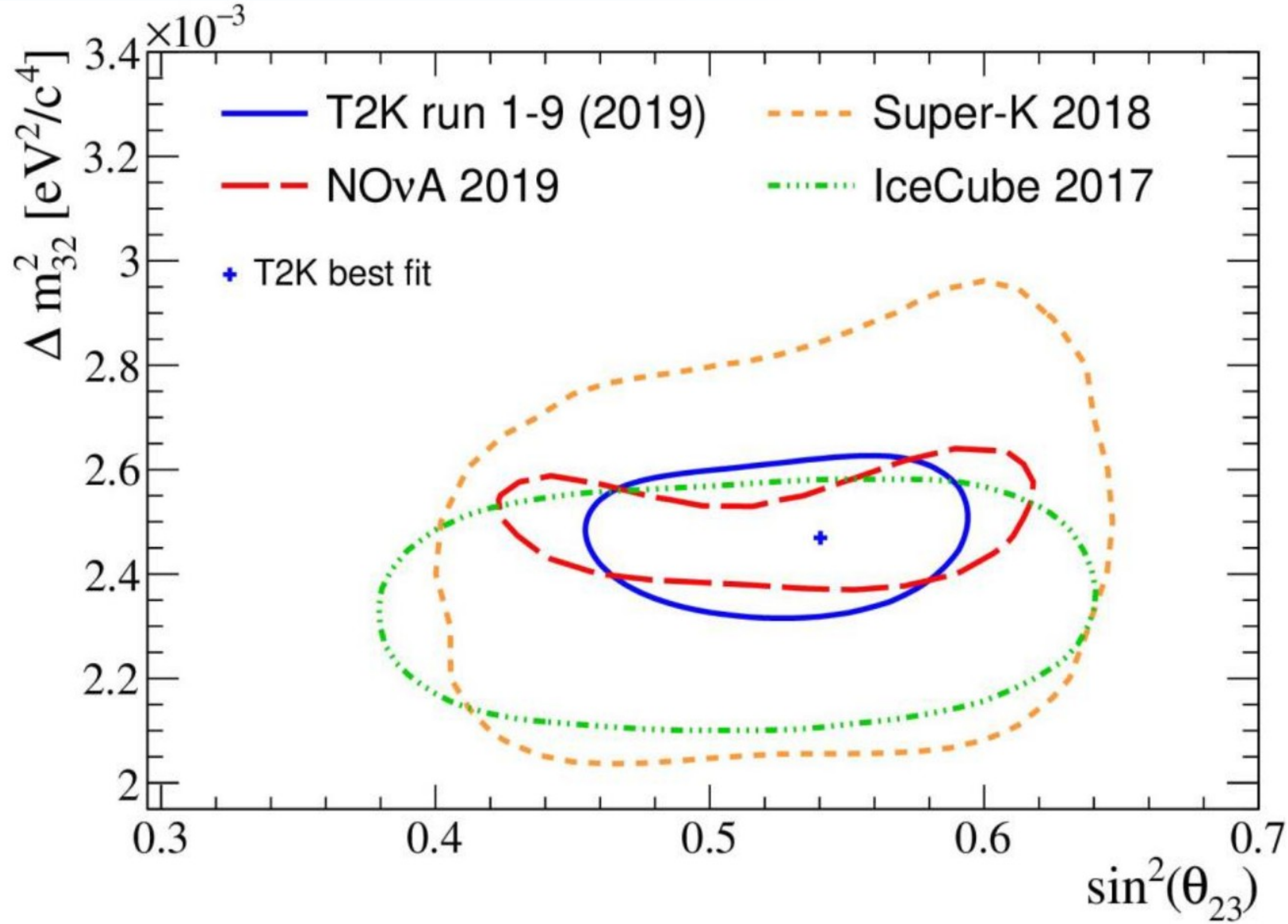


Comparison of current and future experiments

	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) + Intermidiate
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 >3σ	will reach >2σ	will reach >5σ	will reach >5σ
timescale	2010-2026	2014-~2025	~2025-	~2027-

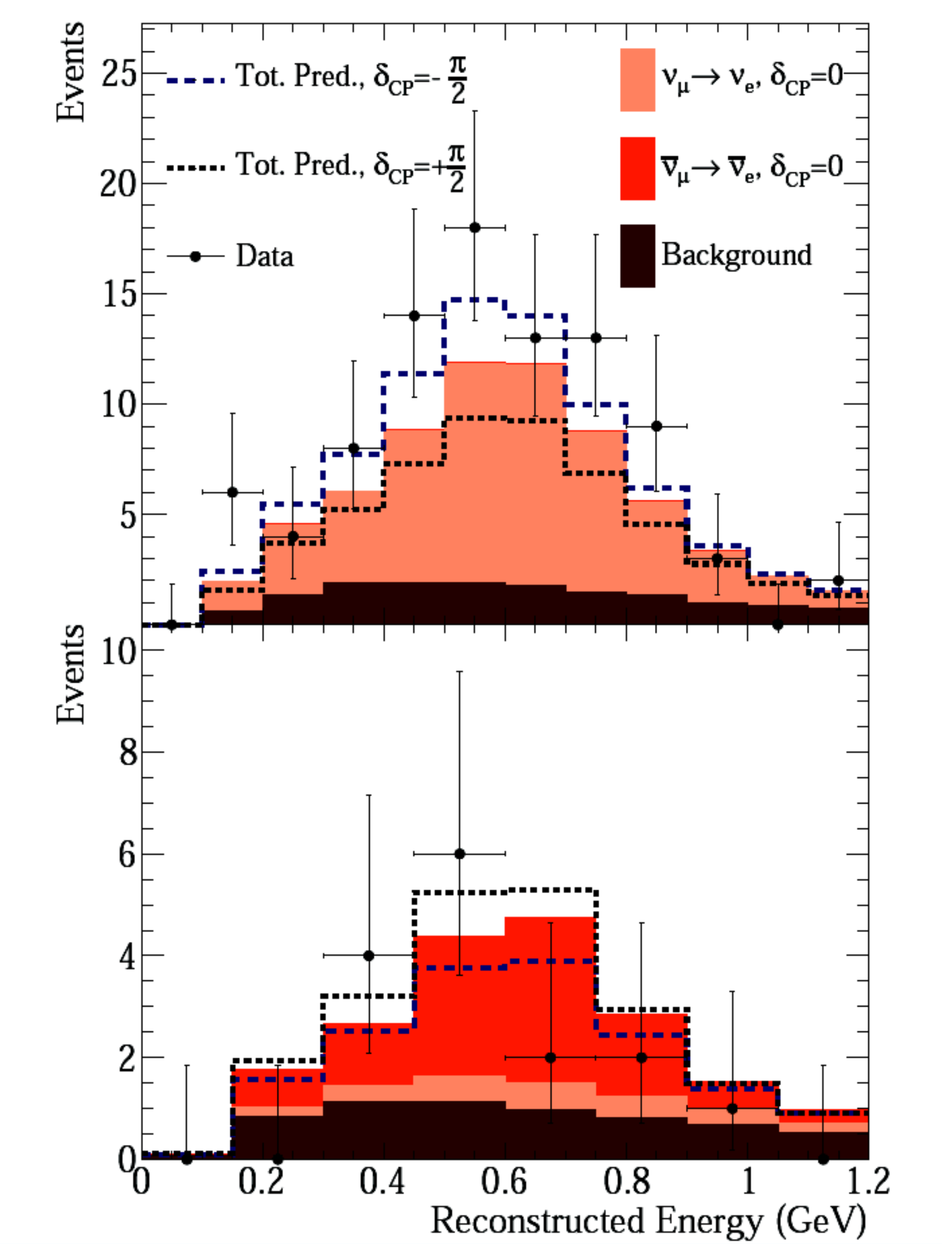
Summary

- The CP symmetry in neutrino sector can be studied by comparing the oscillation probabilities for neutrinos and antineutrinos.
- Current T2K data indicates CP violation at the 2σ confidence level, while NOvA results are consistent with CP conservation. Normal Hierarchy is favored.
  - New oscillation results at Neutrino 2020?
- The T2K collaboration is preparing for T2K phase-II (2021-2026). NOvA will be operational till ~2025.
- DUNE and Hyper-Kamiokande are expected to be operational in the mid 2020s and reach 5σ sensitivity to CPV after a few years of data taking.



$\times10^{-3}$
Δm^2_{32} [eV^2/c^4]
3.4
3.2
3
2.8
2.6
2.4
2.2
2
T2K run 1-9 (2019)
NOvA 2019
Super-K 2018
IceCube 2017
T2K best fit
0.3
0.4
0.5
0.6
0.7
$\sin^2(\theta_{23})$

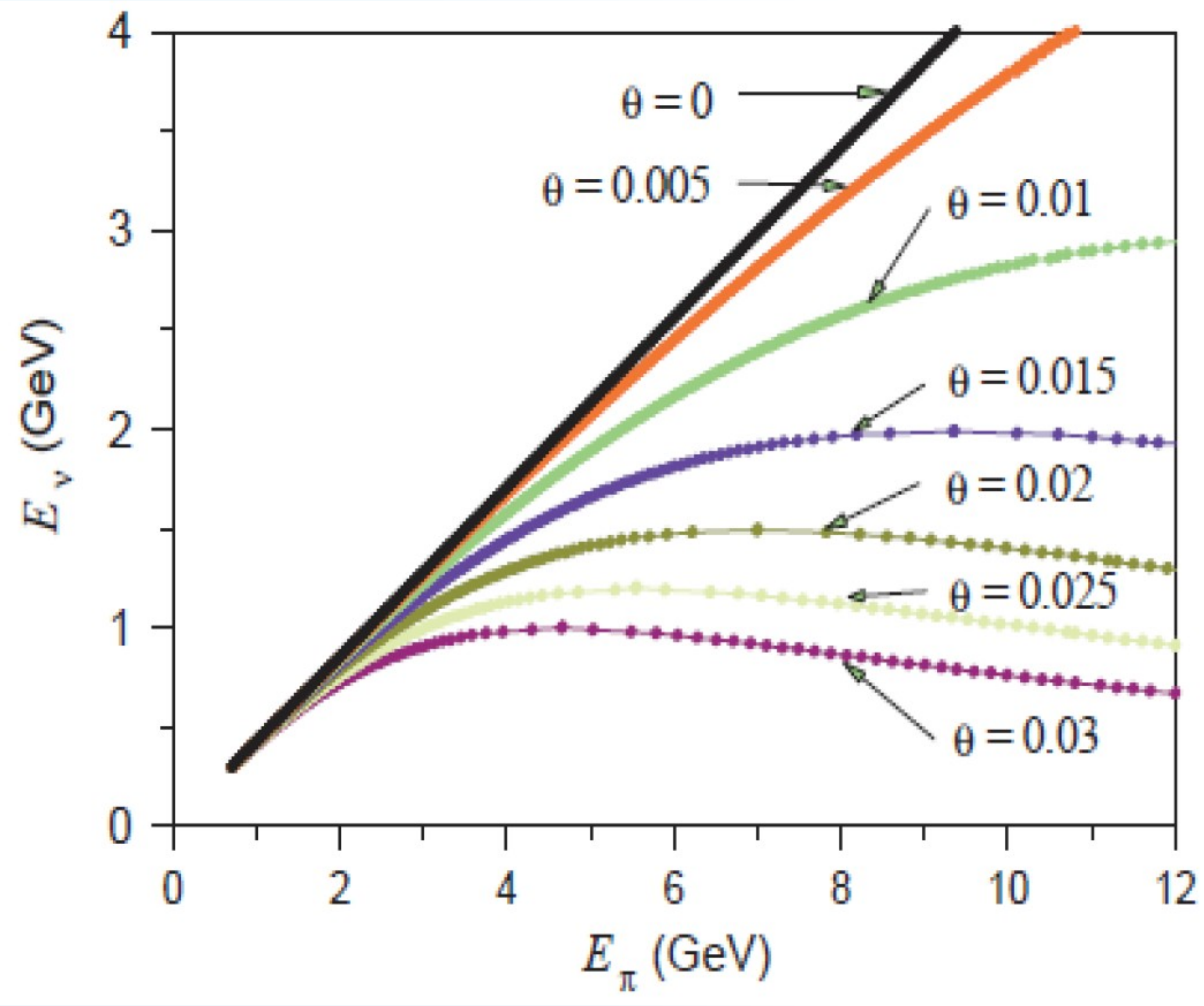
Super-K fit to data



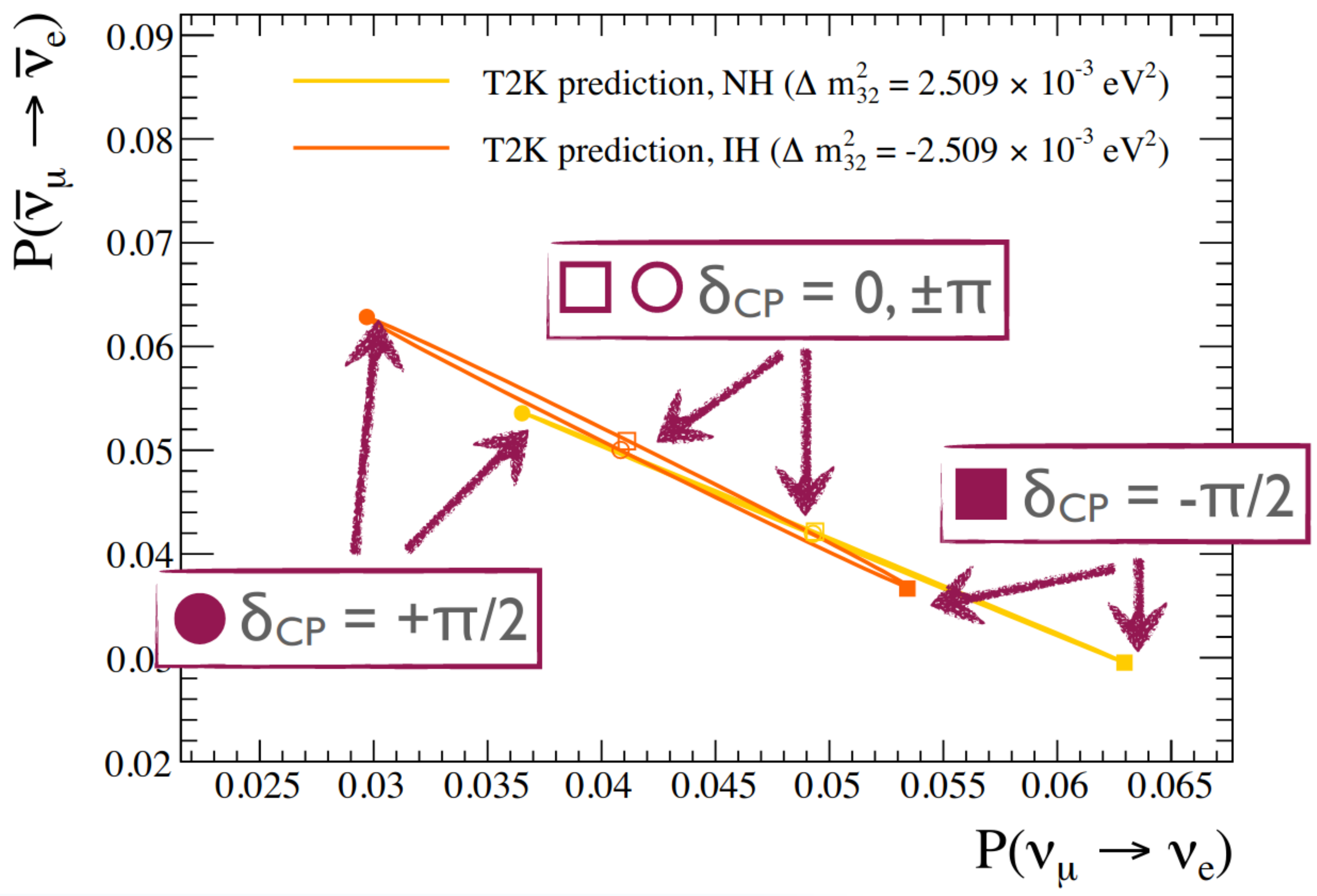
neutrino beam mode

anti-neutrino beam mode

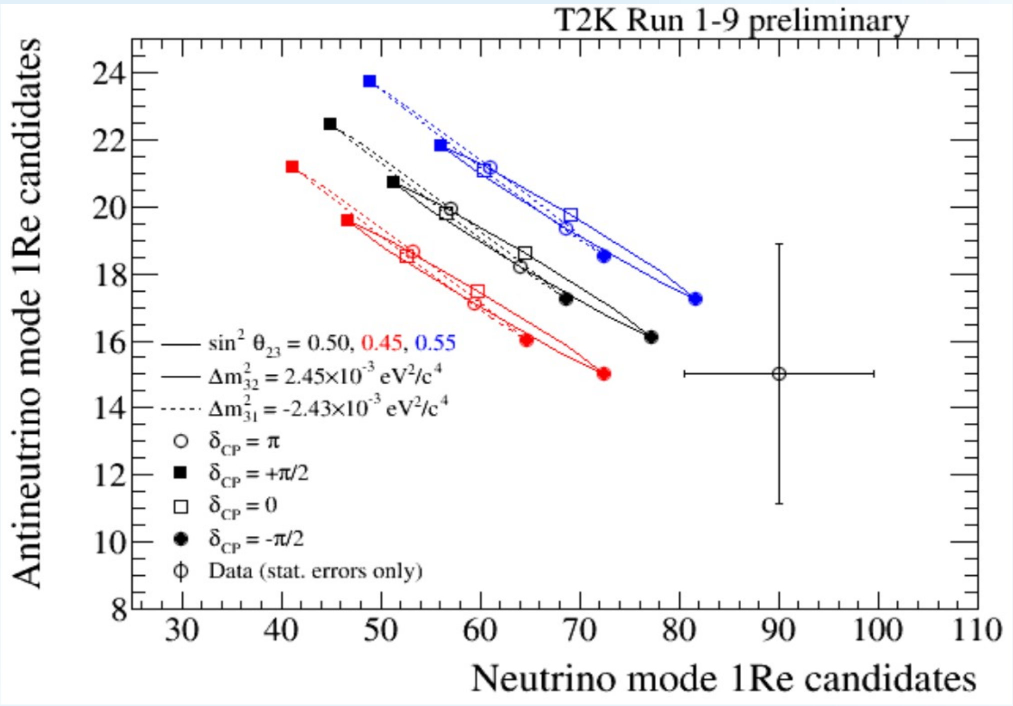
Off-axis beam kinematics

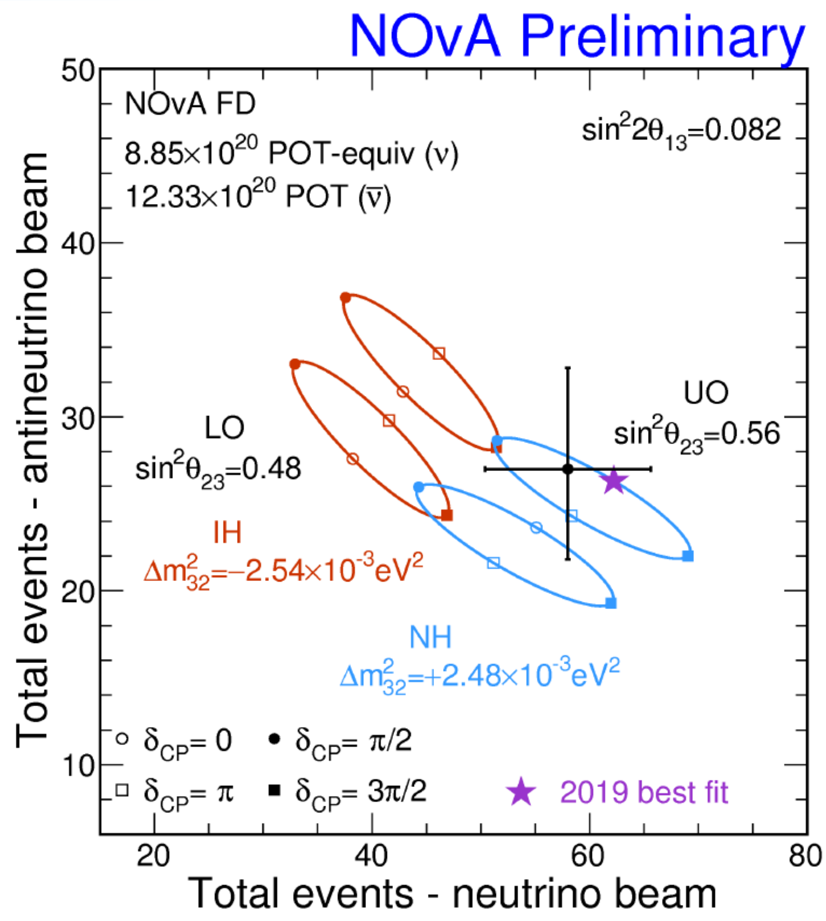


Bi-probability plots



Bi-probability results





Decay channels of neutrino parents

Tabela 2.1: Kanały rozpadów cząstek-rodziców neutrin, rozpady dla cząstek ujemnych są symetryczne ładunkowo [7].

Kanał rozpadu	Prawdopodobieństwo rozpadu (%)
$\pi^+ \to \mu^+ \nu_\mu$	99.9877
$\pi^+ \to e^+ \nu_e$	$1.23 \cdot 10^{-4}$
$K^+ \to \mu^+ \nu_\mu$	63.55
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3.353
$K^+ \to \pi^0 e^+ \nu_e$	5.07
$K_L^0 \to \pi^- \mu^+ \nu_\mu$	27.04
$K_L^0 \to \pi^- e^+ \nu_e$	40.55
$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$	100

What happens when matter appears?

- The additional term in the Hamiltonian is a result of different scattering of ν_e and $\nu_{\mu,\tau}$ neutrinos (and antineutrinos).

- ν_e may scatter via CC and NC interaction

- $\nu_{\mu,\tau}$ may scatter only via NC interaction