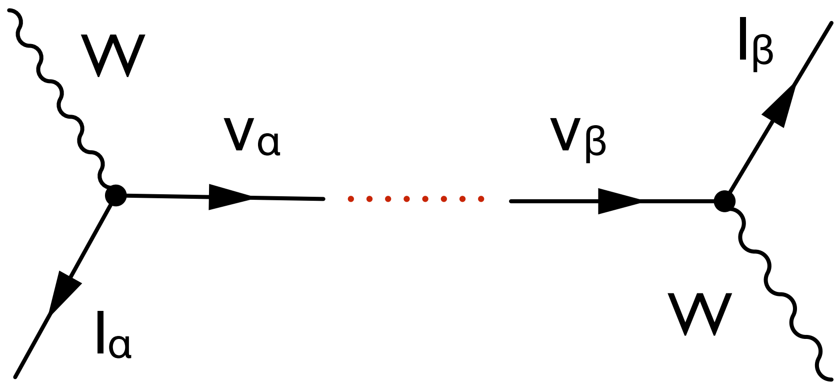
T2K latest oscillation analysis and cross-section results

Lorenzo Magaletti (Politecnico di Bari & INFN Bari)
On behalf of the T2K collaboration

NNN23: 22nd International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

11th October 2023

Mixing of three neutrinos



Neutrinos produced in weak processes (ν_α) are linear combinations of mass eigenstates (ν_i)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

where **U** is the **Pontecorvo-Maki-Nakagawa-Sakata (PMNS)** matrix

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

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

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

Super-K, SNO, KamLAND

$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$
(PMNS Neglecting possible Majorana phases)

Current knowledge:

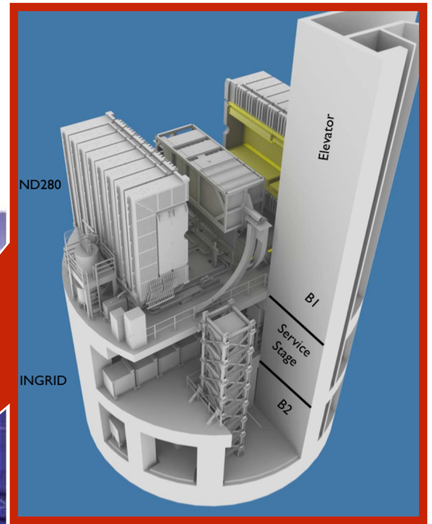
- $\theta_{12} \approx 33^\circ$
- $\theta_{23} \approx 45^\circ$
- $\theta_{13} \approx 9^\circ$
- $\Delta m^2_{21} \approx 7.5 \times 10^{-5}$ eV^2
- $|\Delta m^2_{31}| \approx 2.4 \times 10^{-3}$ eV^2

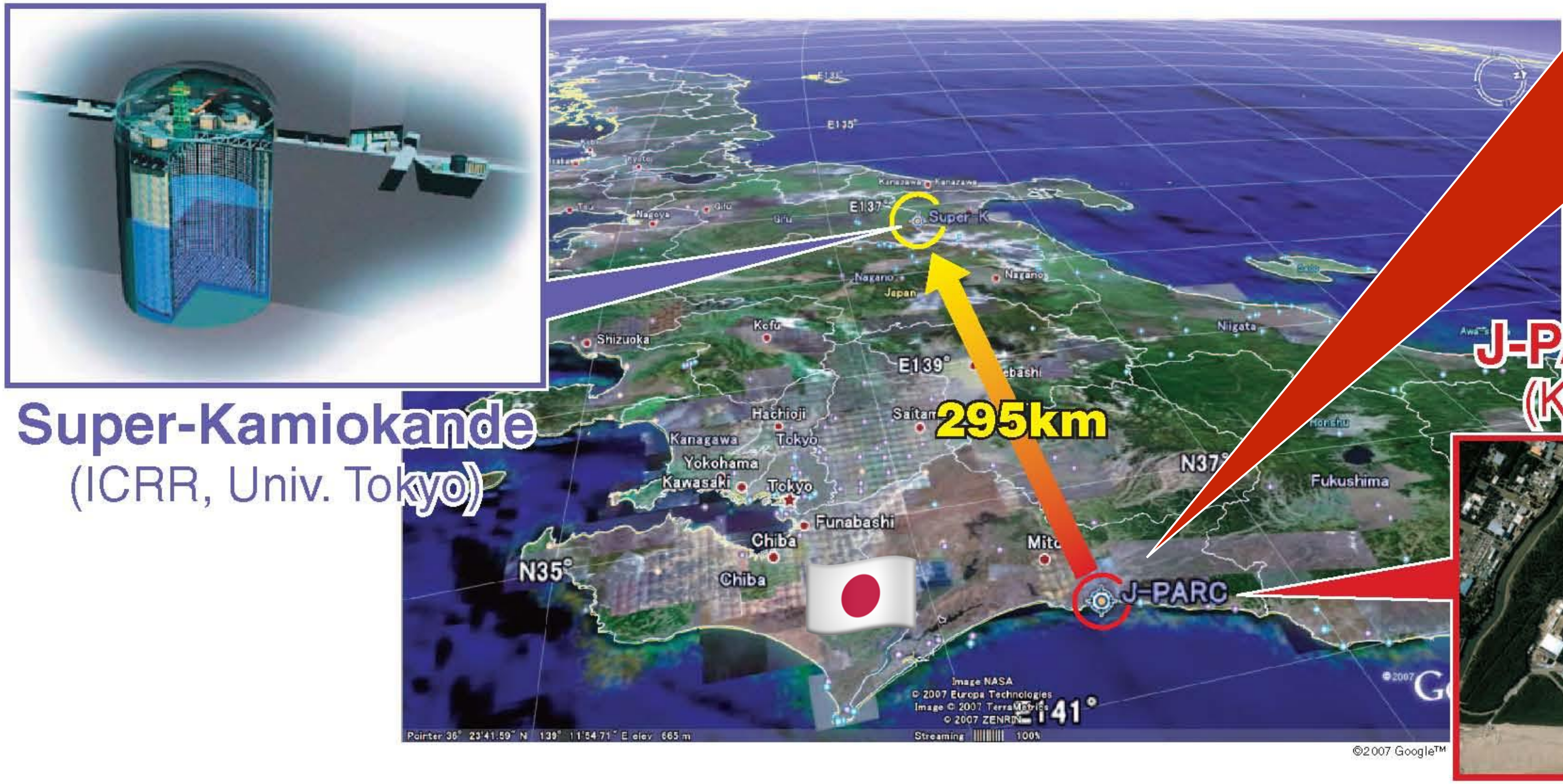
Open questions:

- CP violation?
- Mass hierarchy ($m_{1,2} \gtrless m_3$)?
- Is $\theta_{23} = 45^\circ$?
- Majorana/Dirac? ($0\nu\beta\beta$)

Neutrino oscillations at T2K

Near detector complex
at 280 m from the target





J-PARC Main Ring
(KEK-JAEA, Tokai)

Intense high purity muon (anti)neutrino beam from J-PARC to Super-K to study:

- Muon (anti) neutrino disappearance $\nu_\mu \nrightarrow \nu_\mu$ ($\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$)
- Electron (anti) neutrino appearance $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
- Rich program of:
  - neutrino cross sections studies with near detectors
  - “exotic” physics: sterile neutrinos, etc…

Big international collaboration of neutrino LBL

~575 physicists, 75 institutions, 14 countries

Canada
TRIUMF
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

CERN

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
Keio U.
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tohoku U.
Tokyo Institute Tech
Tokyo Metropolitan U.
Tokyo U of Science
U. Tokyo
Yokohama National U.
ILANCE

United Kingdom
Imperial C. London
King's College London
Lancaster U.
Oxford U.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
U. Warwick

Hungary
Eötvös Loránd U.

France
CEA Saclay
LLR E. Poly.
LPNHE Paris

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid
U. Sevilla

Germany
RWTH Aachen
Universität Mainz

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U.T.
Wrocław U.

Russia
INR
JINR

USA
Boston U.
Colorado S. U.
Duke U.
U. Houston
Louisiana State U.
Michigan S.U.
SLAC
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pennsylvania
U. Pittsburgh
U. Rochester
U. Washington

ITALY
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Switzerland
ETH Zurich
U. Bern
U. Geneva

Vietnam
IFIRSE
Hanoi Univ. Science

Neutrino appearance and disappearance at T2K

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\Delta m^2_{31}\frac{L}{4E}$$

- Precision measurement of θ_{23} and Δm^2_{31}
- CPT test with anti-neutrino mode ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)

$$\begin{aligned}
P(\nu_\mu \to \nu_e) = \; & 4c^2_{13}s^2_{13}s^2_{23}\sin^2\frac{\Delta m^2_{13}L}{4E_\nu} \times \left[1 \pm \frac{2a}{\Delta m^2_{13}}(1 - s^2_{13})\right] \\
& + 8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23})\cos\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\sin\frac{\Delta m^2_{12}L}{4E\nu} \\
& \mp 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta_{CP}\sin\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\sin\frac{\Delta m^2_{12}L}{4E_\nu} \\
& + 4s^2_{12}c^2_{13}(c^2_{13}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta_{CP})\sin\frac{\Delta m^2_{12}L}{4E_\nu} \\
& \mp 8c^2_{12}s^2_{13}s^2_{23}\cos\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\frac{aL}{4E_\nu}(1 - 2s^2_{13})
\end{aligned}$$

θ13 driven / CP even / CP odd / Solar driven / Matter effect (CP odd)

Change sign by changing ν with $\bar{\nu}$

B. Richter, SLAC-PUB-8587

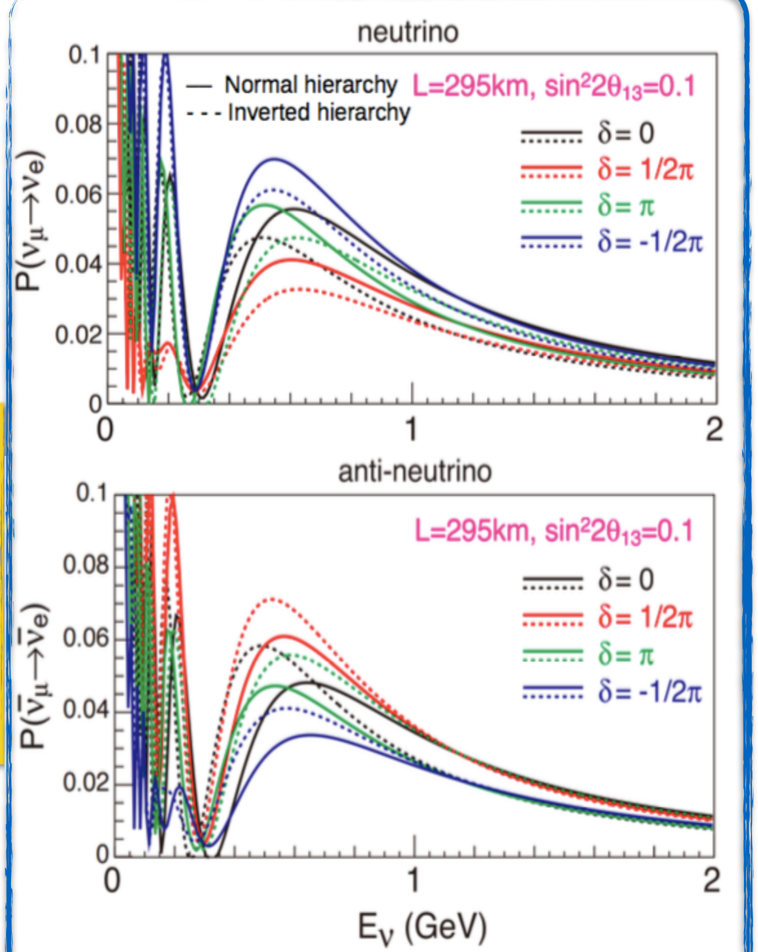
$a[\mathrm{eV}^2] = 2\sqrt{2}G_F n_e E_\nu = 7.6 \times 10^{-5}\rho[\mathrm{g/cm}^2]E_\nu[\mathrm{GeV}]$

- θ_{13} dependence of the leading term
- θ_{23} dependence of the leading term ($\theta_{23}=45^\circ$ or $\theta_{23}\gtrless 45^\circ$?)
- ➤ **CP violation**: asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if $\sin\delta \neq 0$
- Matter effect: ν_e ($\bar{\nu}_e$) appearance enhanced in normal (inverted) mass hierarchy

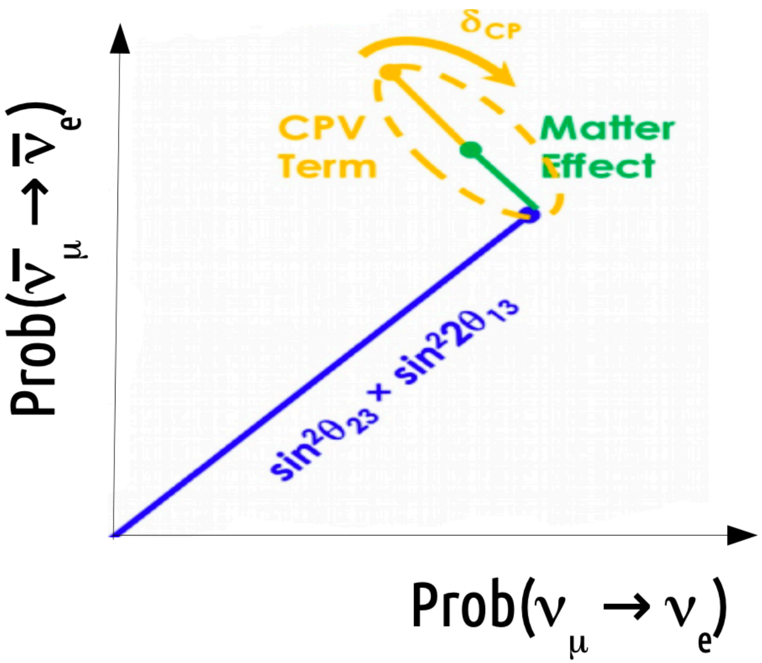
Learning from ν_e ($\bar{\nu}_e$) appearance

- $\sin^2 2\theta_{13}$ and $\sin^2\theta_{23}$ enhance/suppress both ν_e and $\bar{\nu}_e$ appearance

- CP-violating phase δ_{CP} (**up to ±30% effect at T2K**)
  - **δ_{CP} = 0, π**⇒ no CP violation: $P(\nu_\mu\to\nu_e) = P(\bar{\nu}_\mu\to\bar{\nu}_e)$ in vacuum
  - **δ_{CP} ~ -π/2**: enhance $\nu_\mu\to\nu_e$ and suppress $\bar{\nu}_\mu\to\bar{\nu}_e$
  - **δ_{CP} ~ +π/2**: suppress $\nu_\mu\to\nu_e$ and enhance $\bar{\nu}_\mu\to\bar{\nu}_e$



PTEP 2015 (2015) 053C02

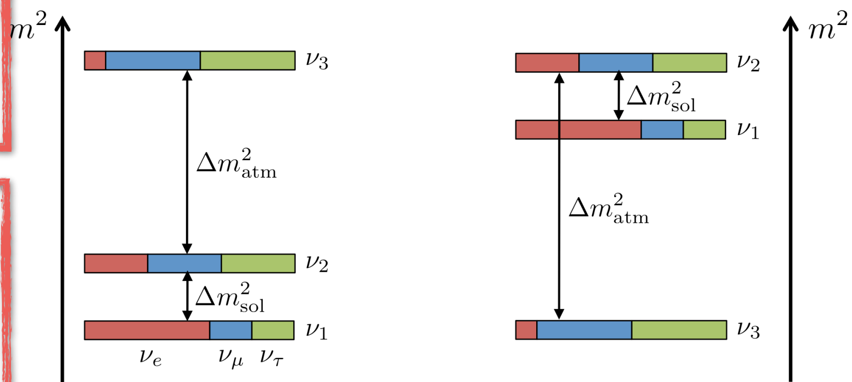


±10% matter effect at T2K

Normal hierarchy
- Enhance $\nu_\mu\to\nu_e$
- Suppress $\bar{\nu}_\mu\to\bar{\nu}_e$

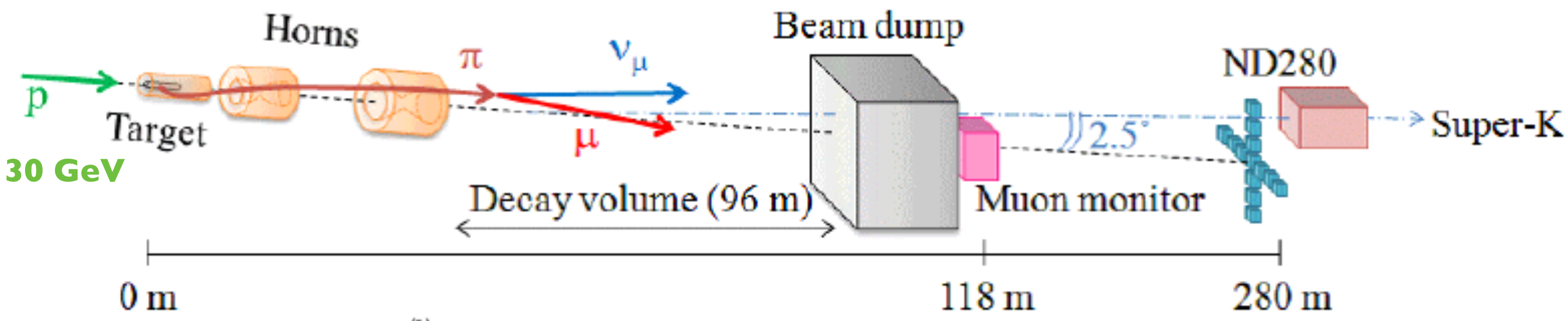
Inverted hierarchy
- Suppress $\nu_\mu\to\nu_e$
- Enhance $\bar{\nu}_\mu\to\bar{\nu}_e$

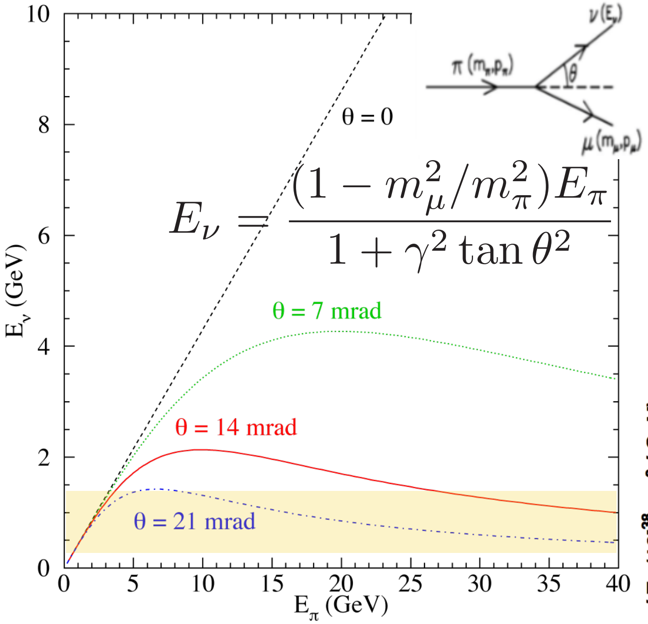
normal hierarchy (NH) **inverted hierarchy (IH)**

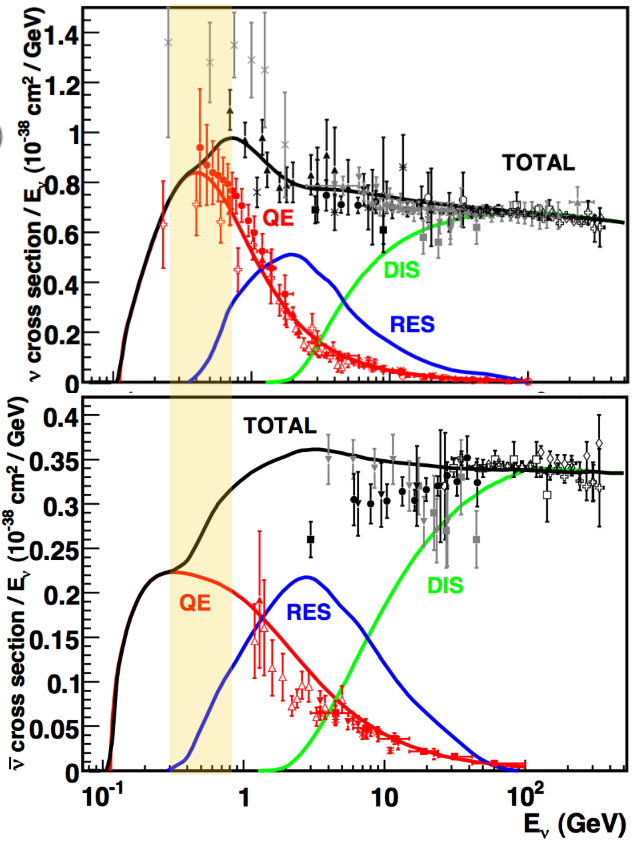


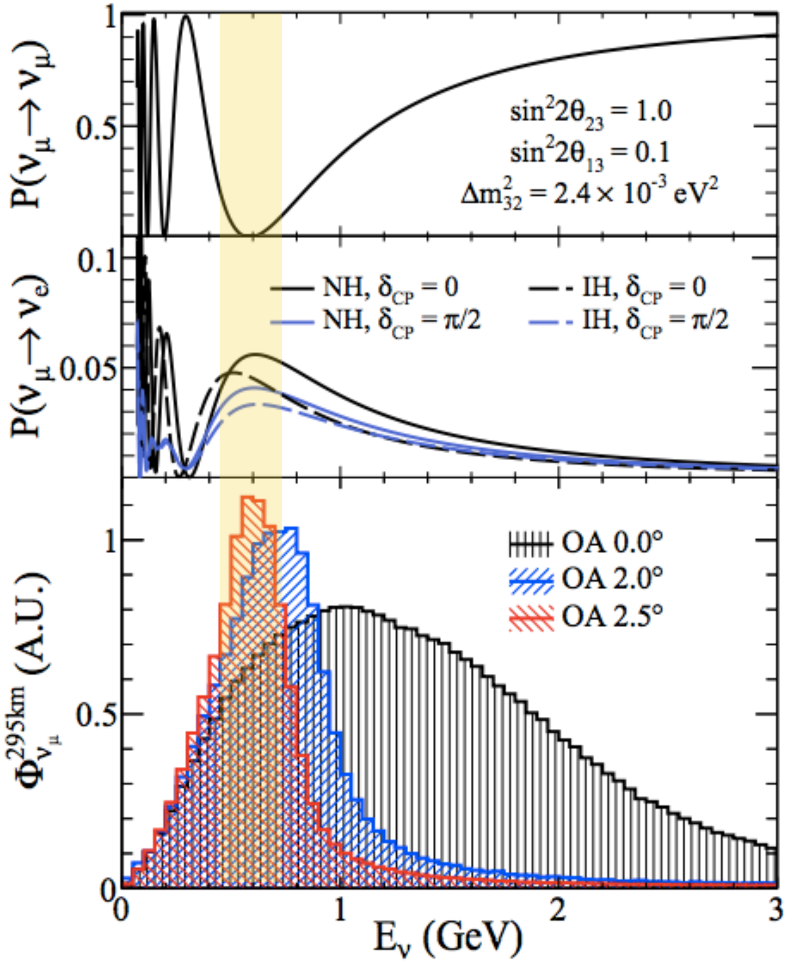
T2K experimental setup

The off-axis neutrino beam







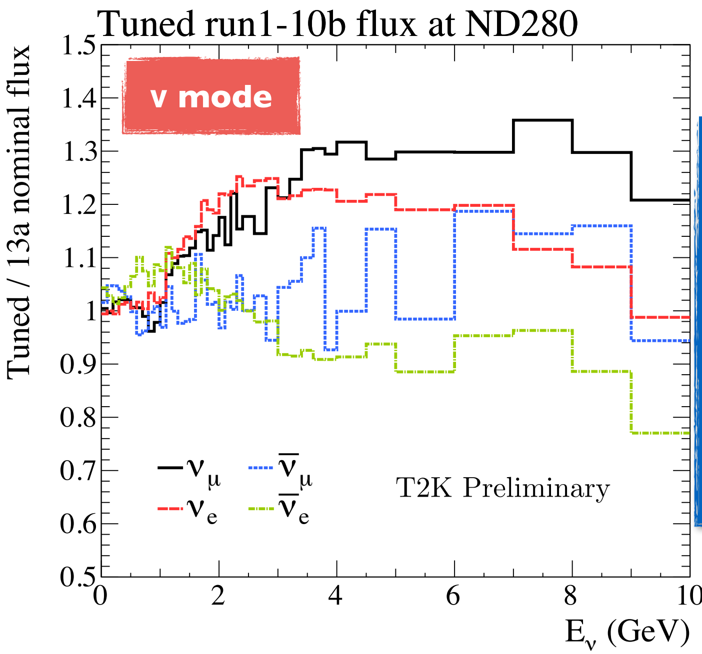


Charged Current Quasi-Elastic (CCQE)

$$\nu_\mu + n \to \mu^- + p$$
$$\bar{\nu}_\mu + p \to \mu^+ + n$$

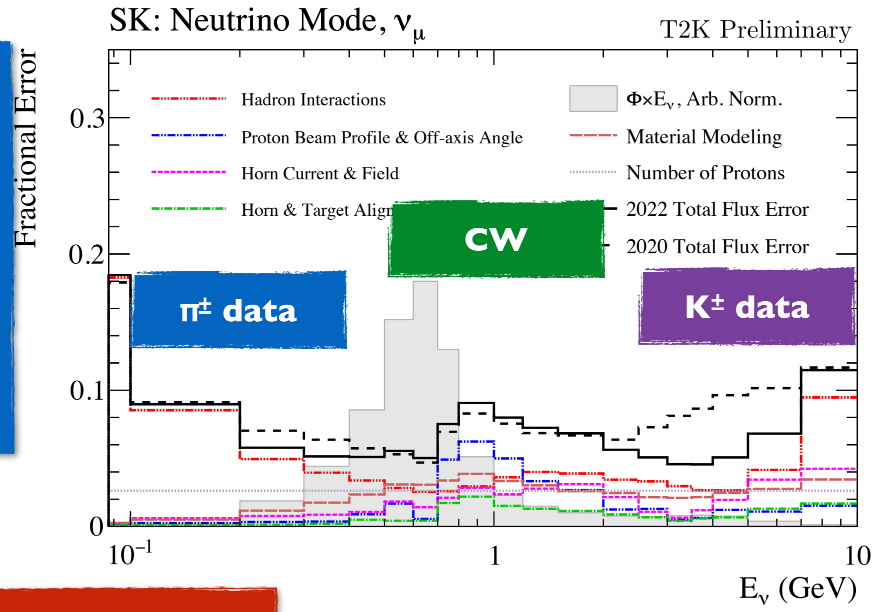
- Enhance neutrino oscillation effects
- Enhance CCQE-like interactions (signal at Super-Kamiokande)
- Reduce background from π^0 interactions

New flux tuning & uncertainty with T2K replica target

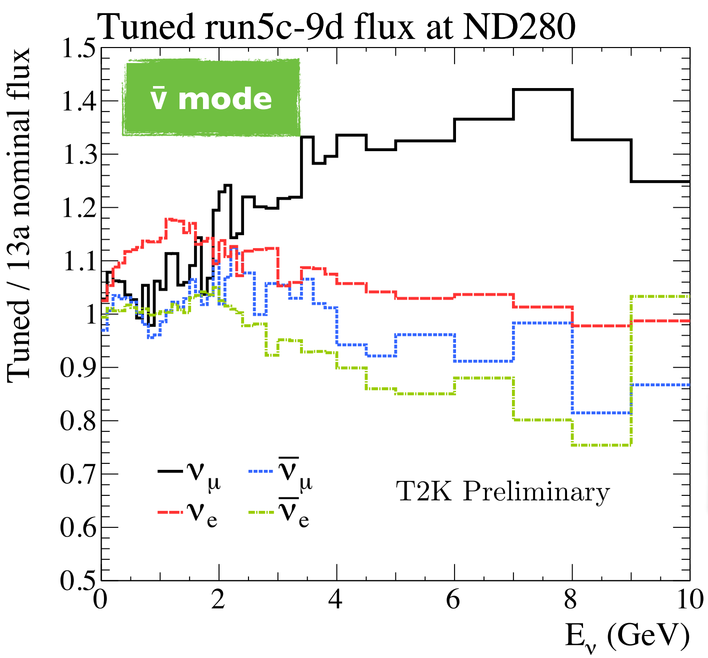


New NA61/SHINE Replica Target Data

- Improved (2020→2022) flux uncertainties
  - ↓ π± data improvements
  - ↑ Cooling water (CW)
  - ↓ K± data improvements



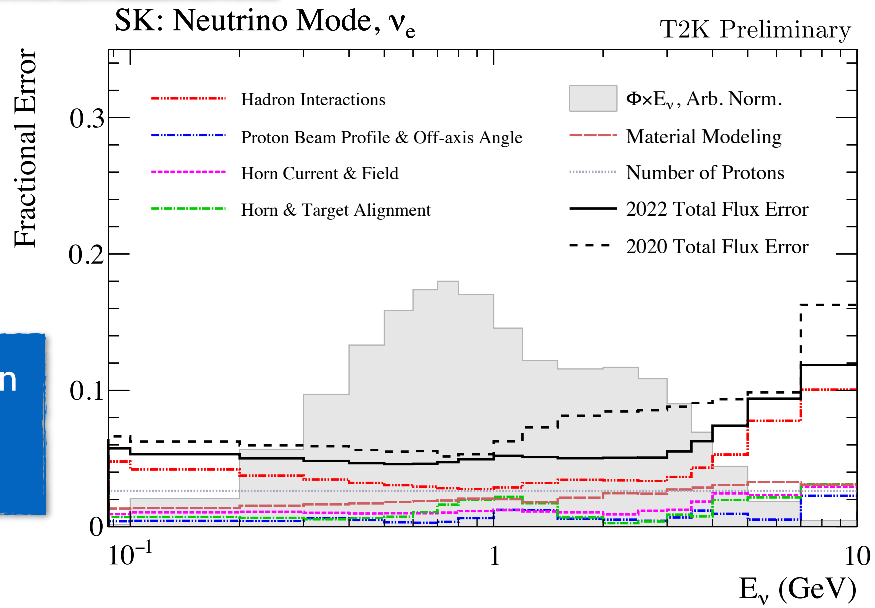
Overall reduction of flux error (by ~6%)



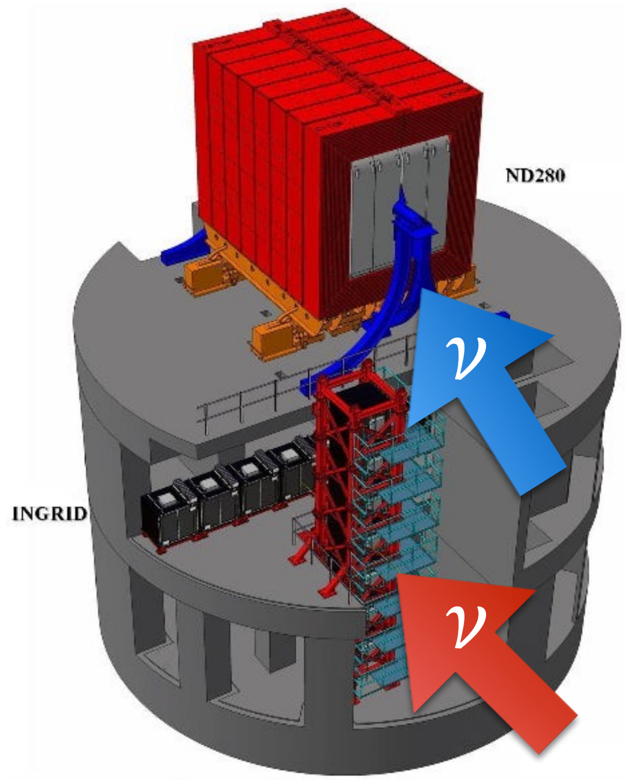
2022 Total Flux Error

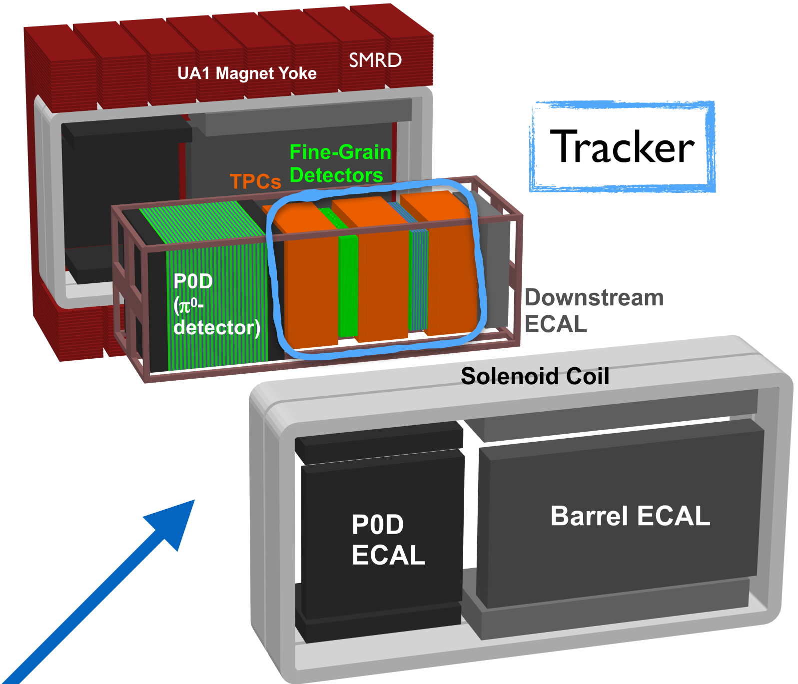
2020 Total Flux Error

Impact of flux tuning based on **replica target** hadron production data



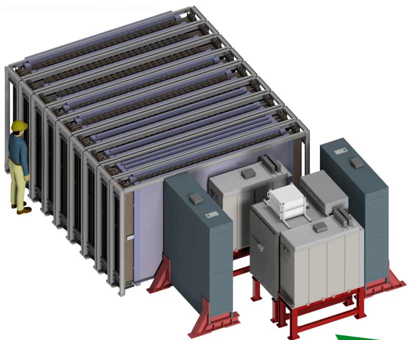
Near Detectors





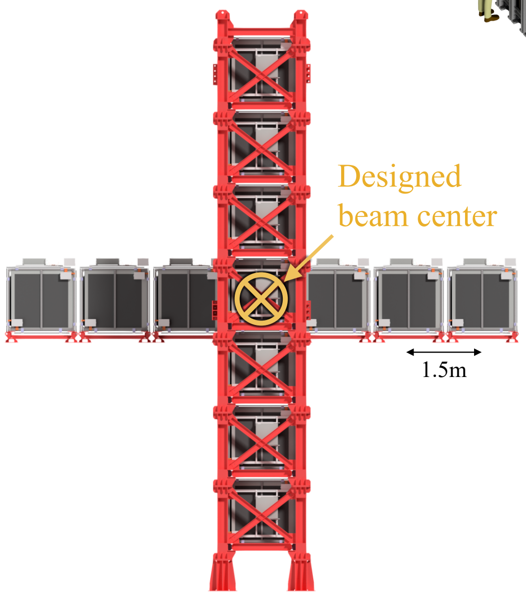
ND280 (off-axis 2.5°)

- **Magnet:** B = 0.2 T
- **TPC:** p measurement + particle-ID with dE/dx
- **FGD:** Fine-grained detectors (2 x 0.8 t) → FGD1 (C), FGD2 (C+H_2O)
- **SMRD:** magnetized muon range detector
- **P0D:** pi-zero detector (Pb/brass-H_2O-scintillator)
- **ECal:** electromagnetic calorimeter



WAGASCI-Baby MIND (off-axis 1.5°)

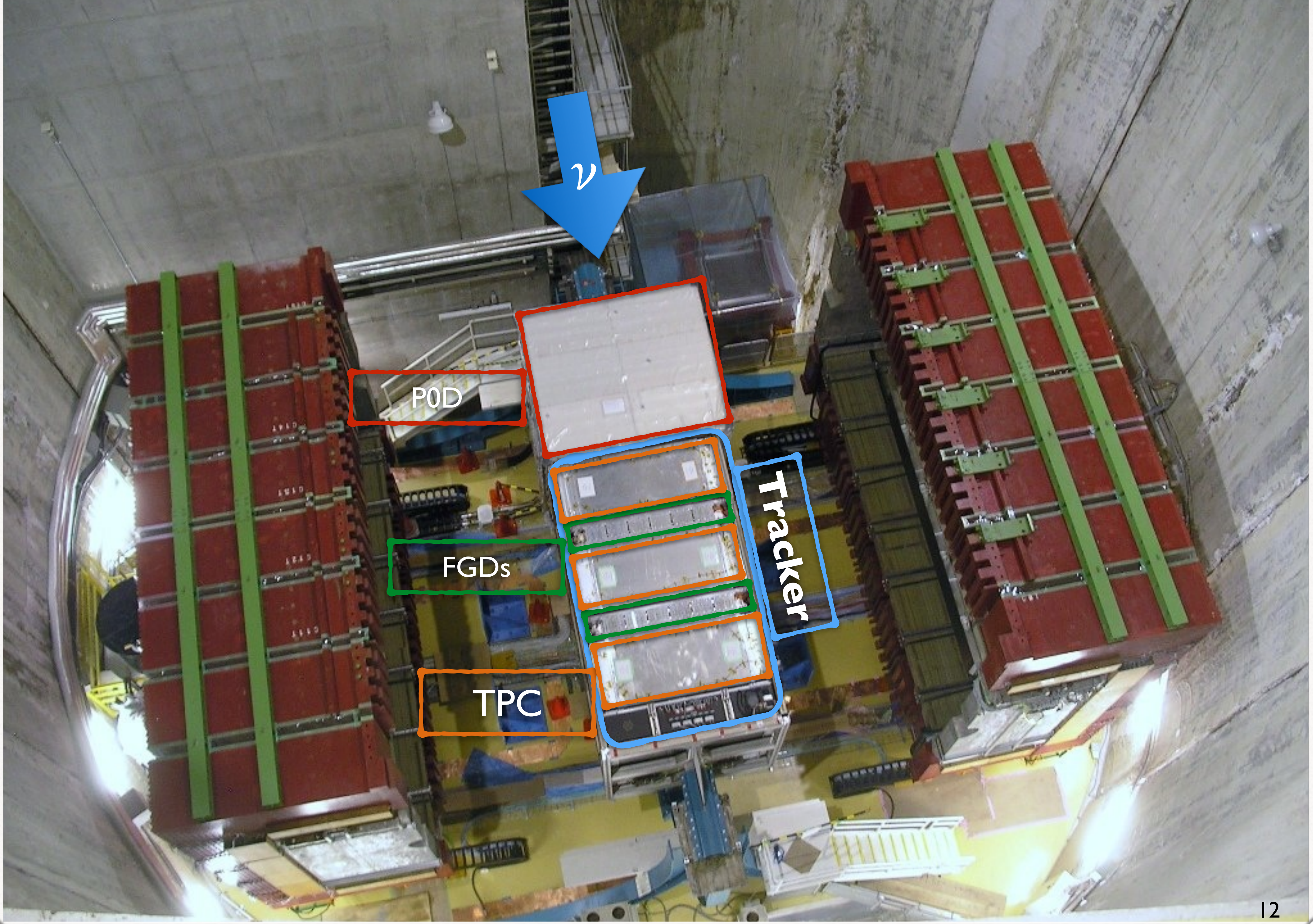
- **WAGASHI**: plastic scintillator detector filled with water (~ 80%)
- **BabyMIND**: magnetised iron and scintillator (μ charge and range)
- **Not used yet in the oscillation analysis**



INGRID (on-axis)

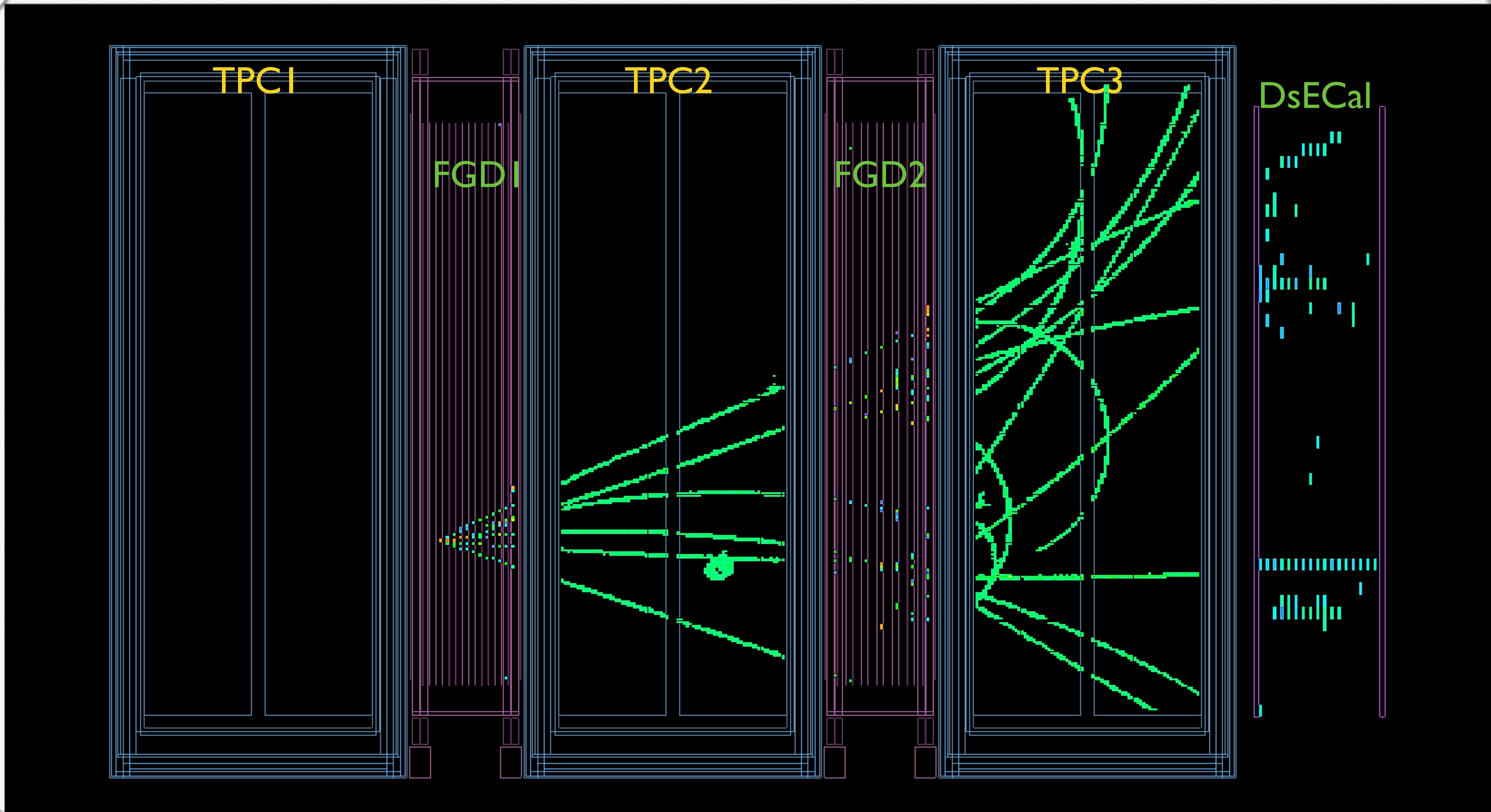
- **ν_μ CC rate → monitor beam profile and stability**
- **Fe/Scintillator tracking calorimeter** (16 Fe/Scint modules + 1 central one made of scintillator only)

The T2K off-axis near detector: ND280

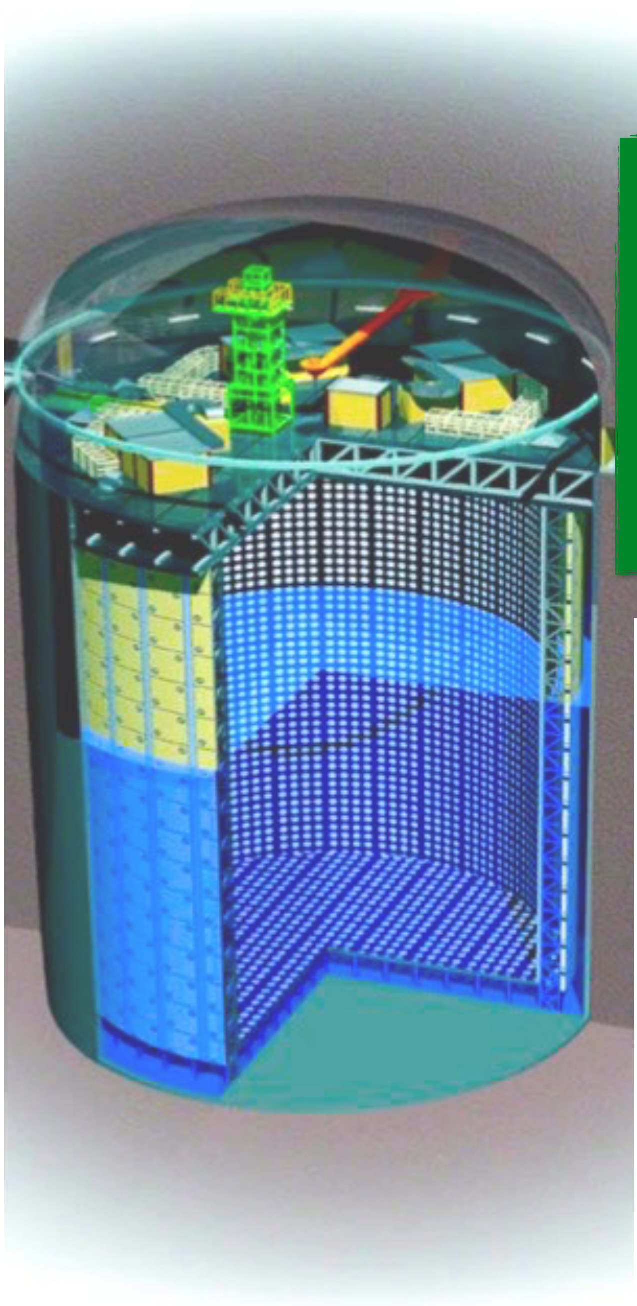


The T2K off-axis near detector: ND280

- ND280 **samples of ν_μ ($\bar{\nu}_\mu$) interactions in Carbon (FGD1) and water (FGD2)** have been employed **in the near detector analysis**.
- **FGD2** samples are useful for a **better cancelation of systematic uncertainties** caused by nuclear effects on neutrino-water cross-sections.
- Possibility to add the **“wrong sign”** samples to better constrain the ν_μ contamination in $\bar{\nu}$ beam mode

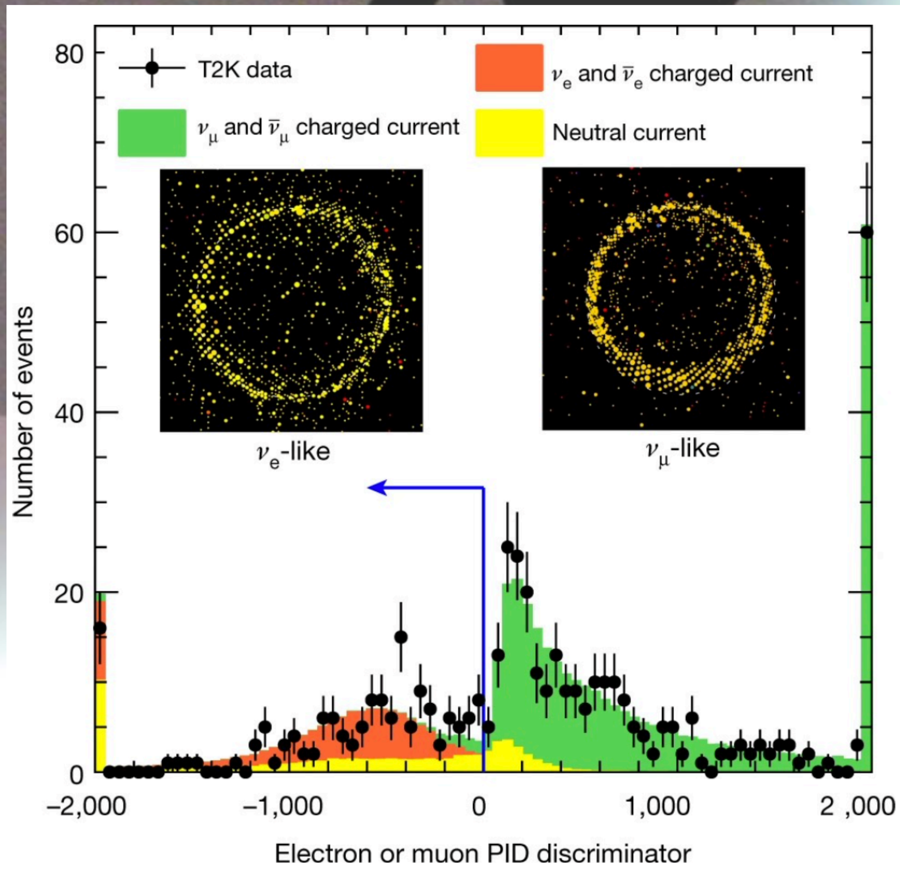


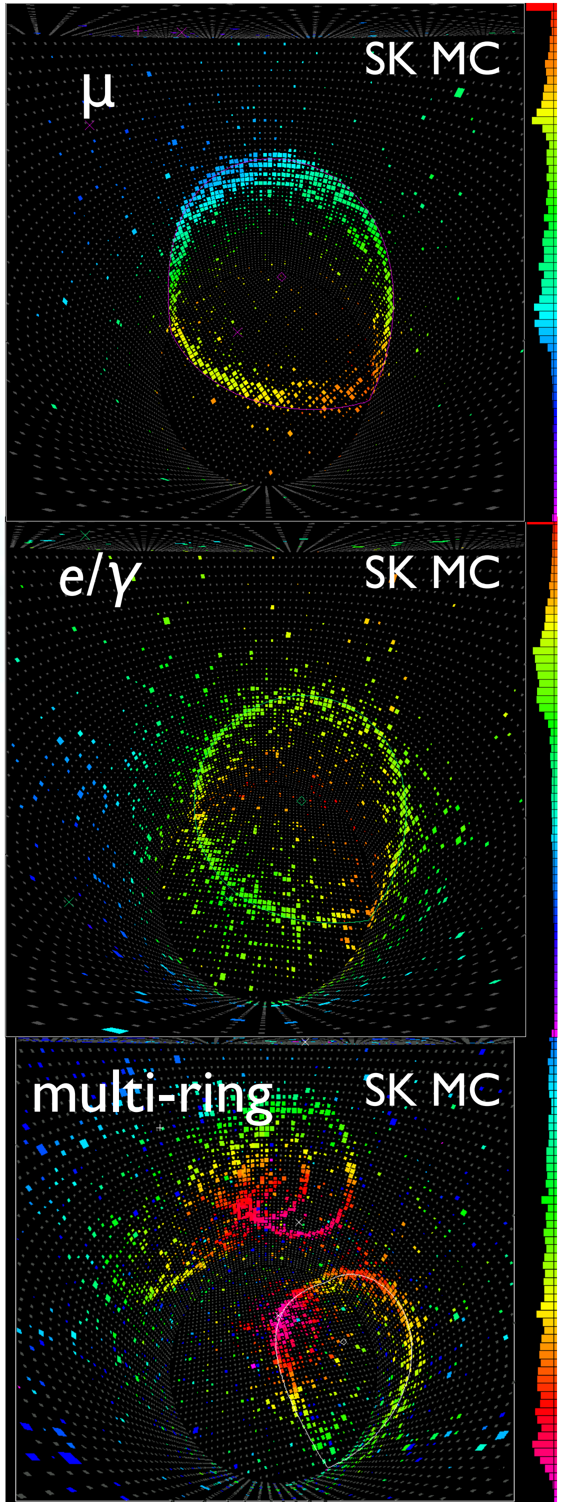
Far detector: Super-Kamiokande



Super-K (2.5° off-axis)

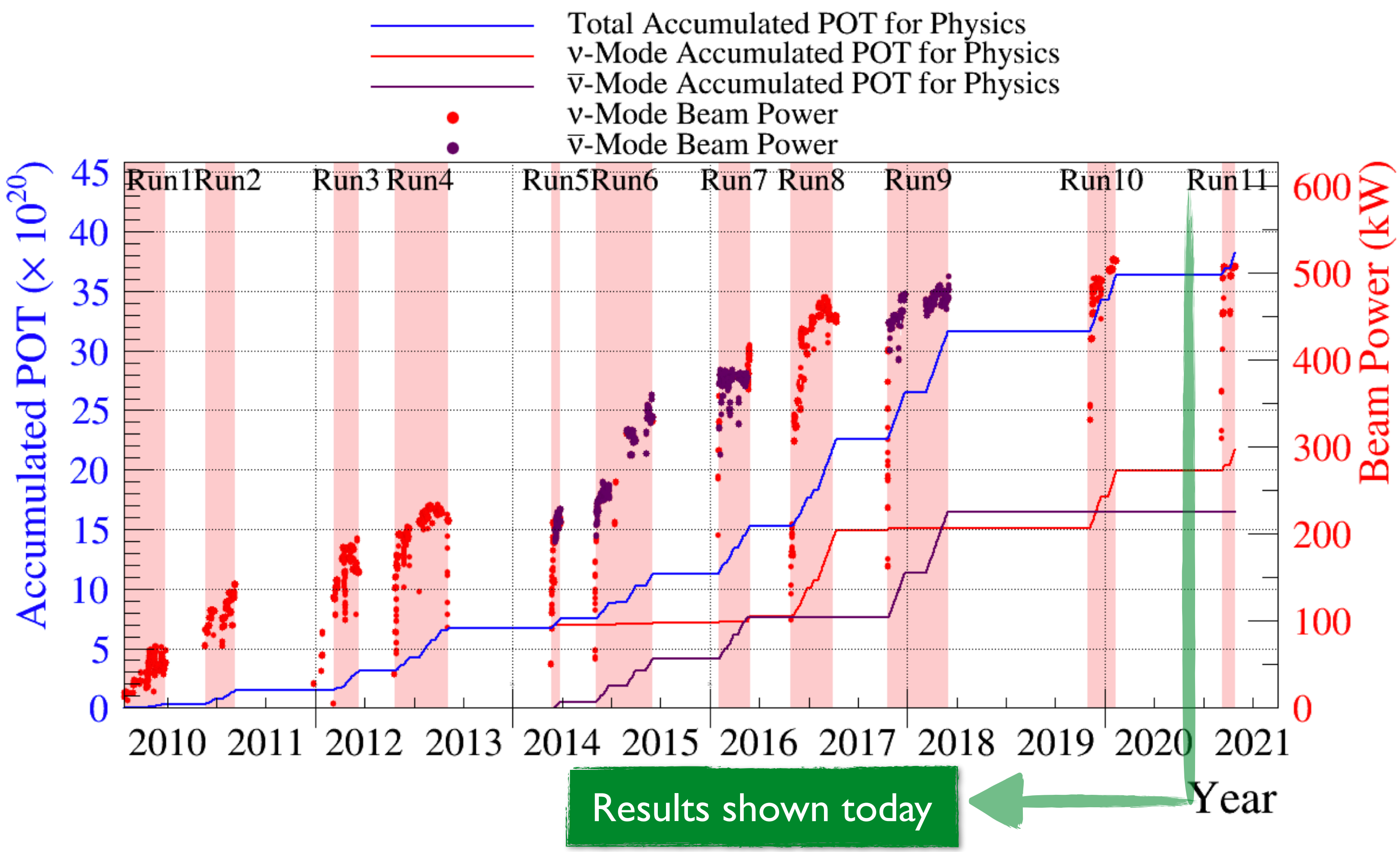
- Water Cherenkov (22.5 kt fiducial volume, > 11k PMT, ~40 m x 40 m)
- Excellent μ/e separation (based on ring profile) and π^0 detection (2 e-like rings)
- <1% mis-PID at 1GeV
- ΔE/E ~10% for Quasi-Elastic (QE) events





T2K oscillation results

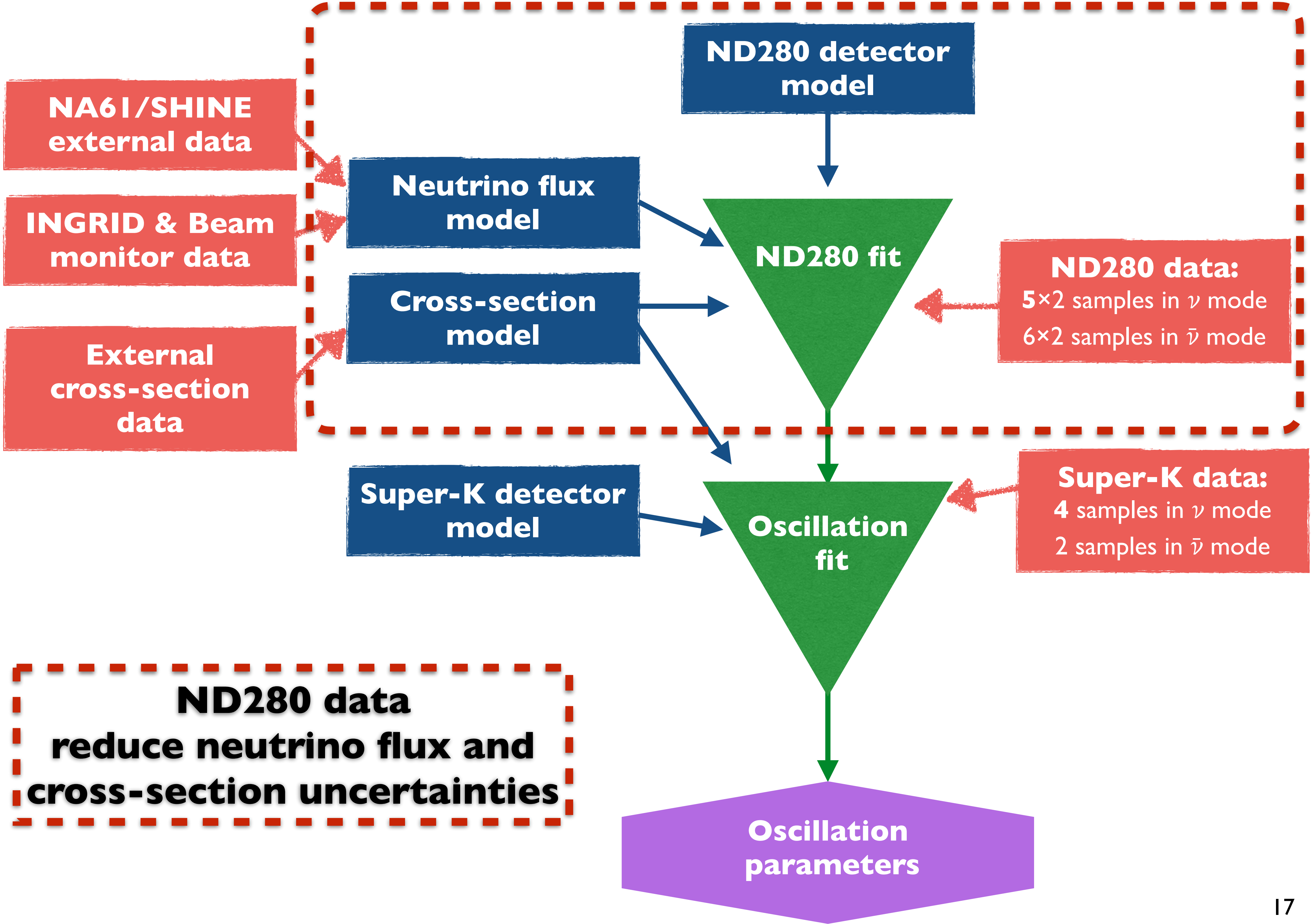
Collected data



Results shown today with **3.6×10^{21} POT**

POT	ND		FD	
Beam Mode	ν	ν̄	ν	ν̄
This Analysis	1.39×10^{21}	0.63×10^{21}	1.97×10^{21}	1.63×10^{21}

Oscillation analysis strategy



ND280 data reduce neutrino flux and cross-section uncertainties

Neutrino cross sections model improvements

- At T2K energies the favoured interactions are **CCQE**
  - Other neutrino interactions with production of **pions** in the final state are important as well
  - **Nuclear effects** can mimic a CCQE interaction

- **Mimic CCQE interactions:**
  - Neutrino scatters on a correlated pair of nucleons (called multi-nucleon or 2 particle-2 hole, **2p-2h**)
  - Neutrino scatter produces a pion, which is re-absorbed in the nucleus
  - Neutrino scatter produces a pion absorbed by the detector

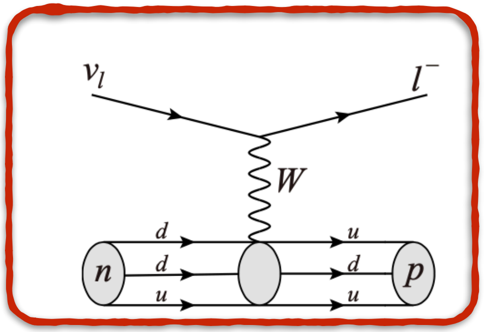
- **CCQE:**
  - Improved uncertainties for the **spectral function** model, specifically normalisation of nuclear shell model and short range correlations.
  - New treatment of **binding energy**.
  - Replaced ad-hoc **Q^2 normalisations** with Pauli blocking

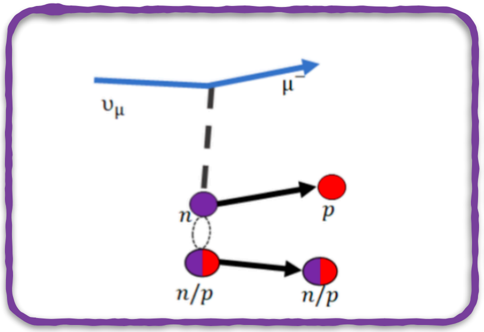
- **2p2h/MEC:**
  - Better descriptions of **2p2h proton-neutron/ neutron-neutron** pair contributions.

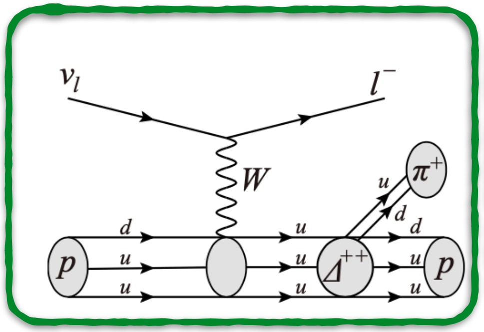
- **CCRes:**
  - New **bubble-chamber tuning of Rein-Sehgal model** parameters.
  - Effective inclusion of **binding energy**.
  - New Δ **resonance decay** uncertainty
  - New uncertainty in **$\pi^{\pm}$** vs **π^0** production

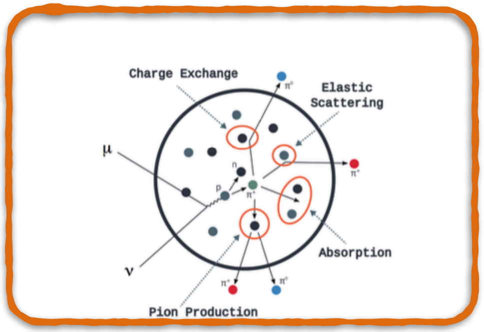
- **FSI:**
  - New nucleon final state interactions (FSI) uncertainty.

link to NuFACT talk on Neutrino interaction models

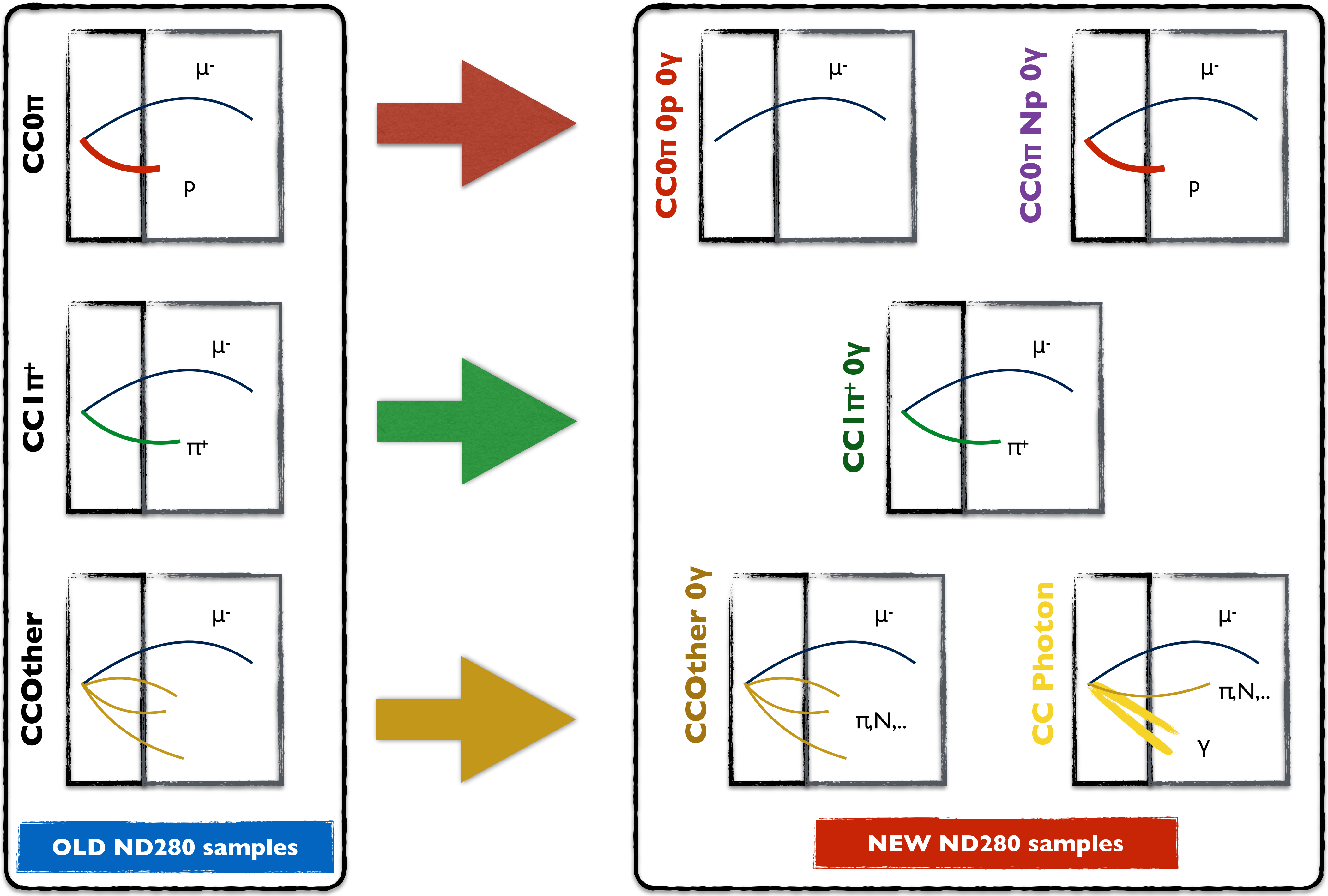




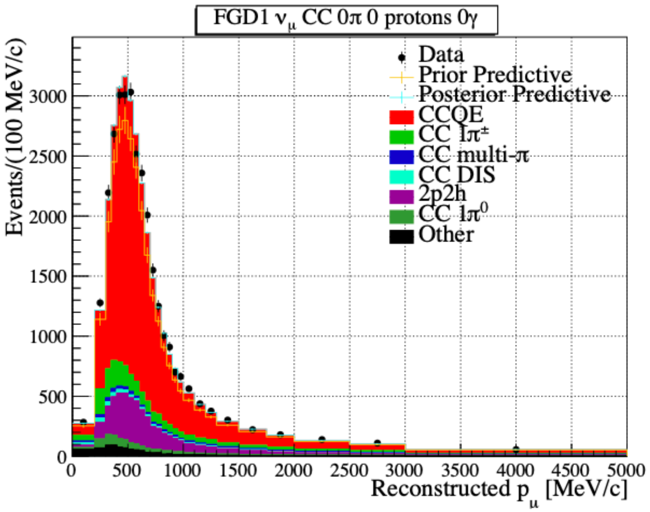


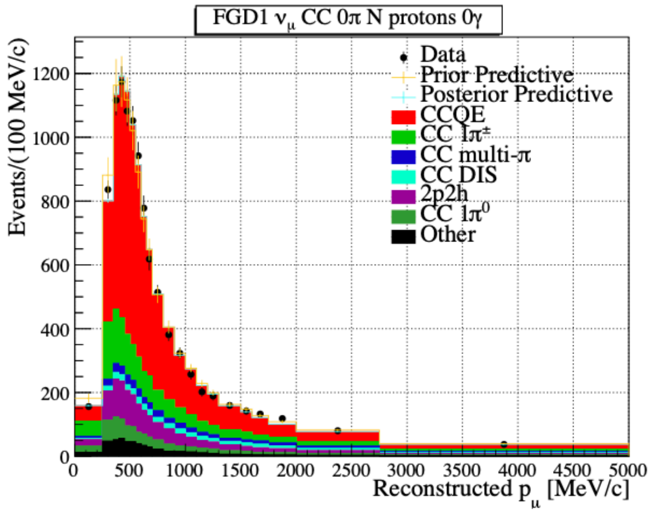


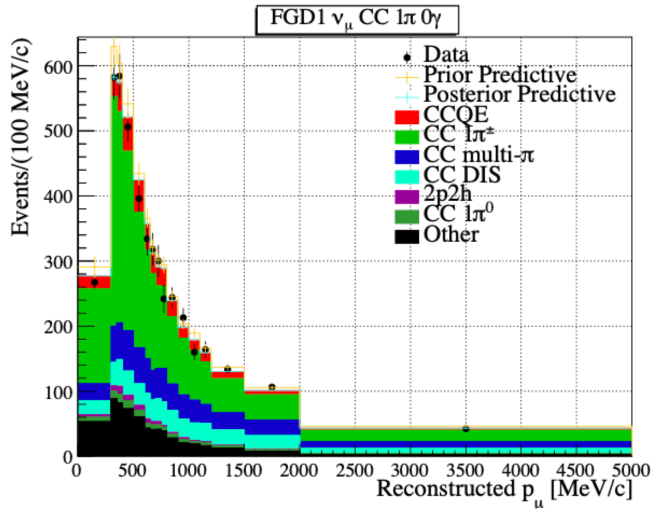
New ND280 samples in neutrino beam mode

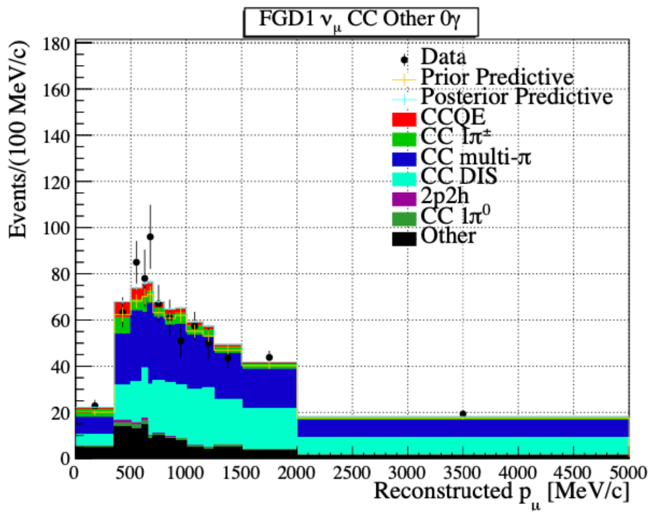


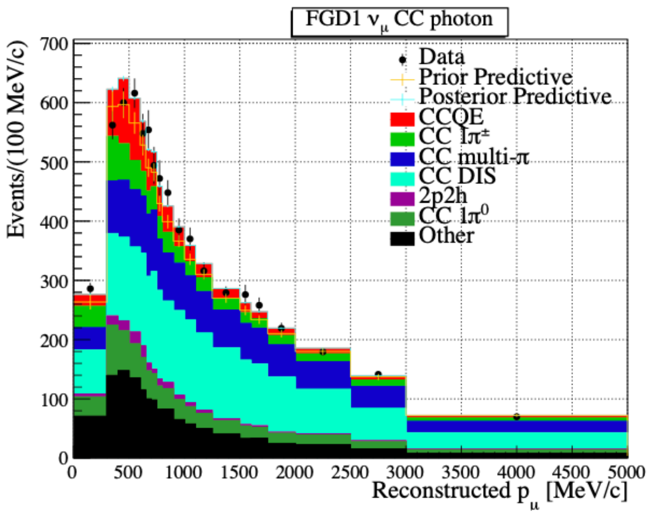
ND280 samples in neutrino beam mode





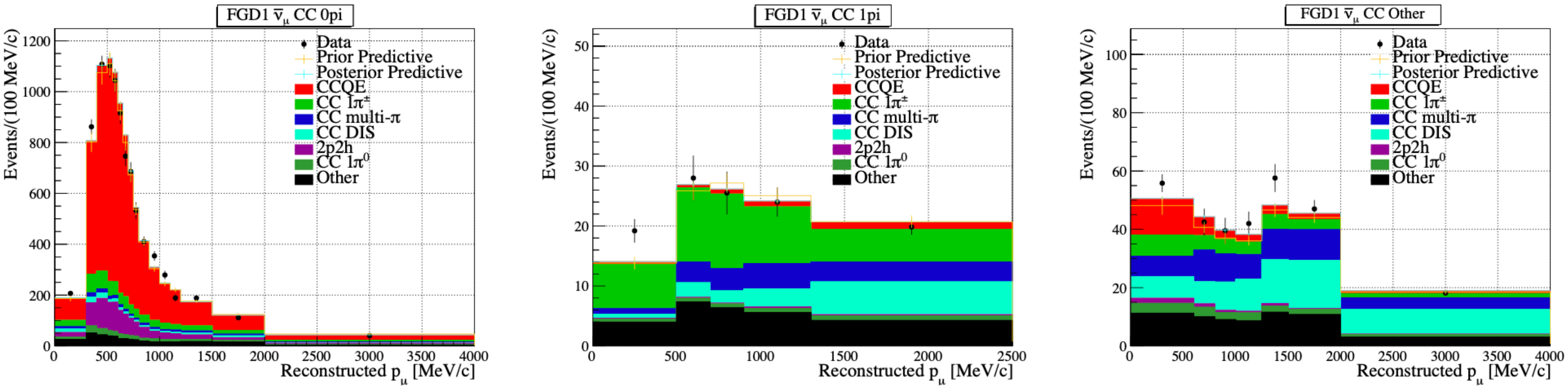




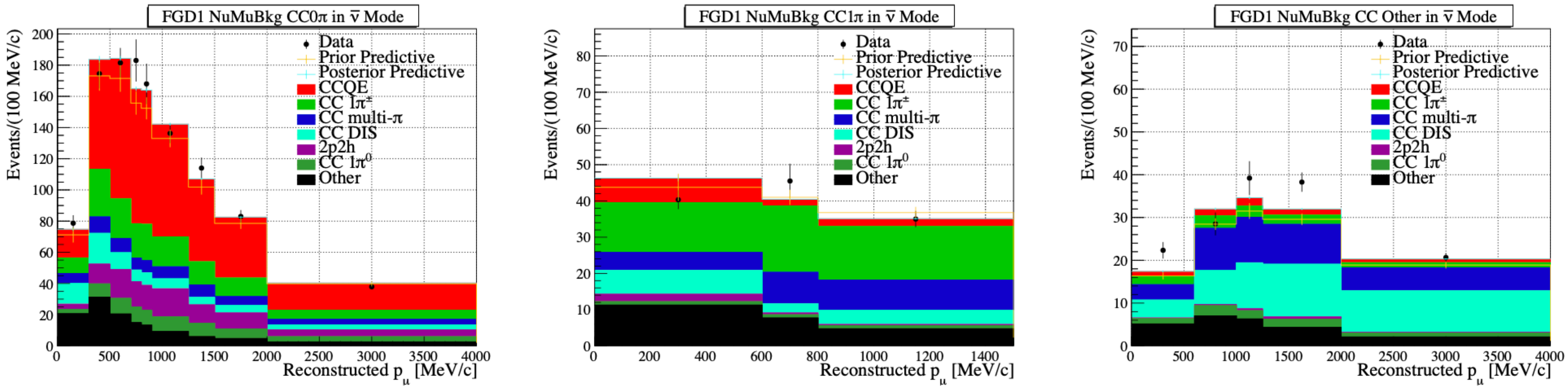


5 × 2 neutrino beam mode ND280 samples used in the oscillation analysis

ND280 samples in neutrino beam mode



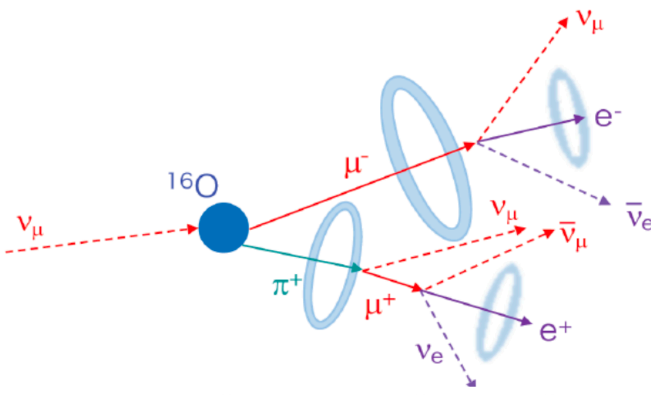
Right sign component

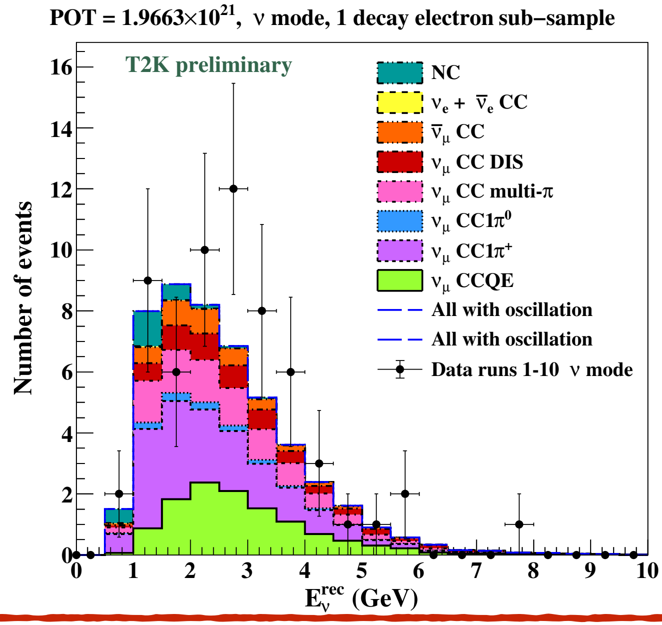


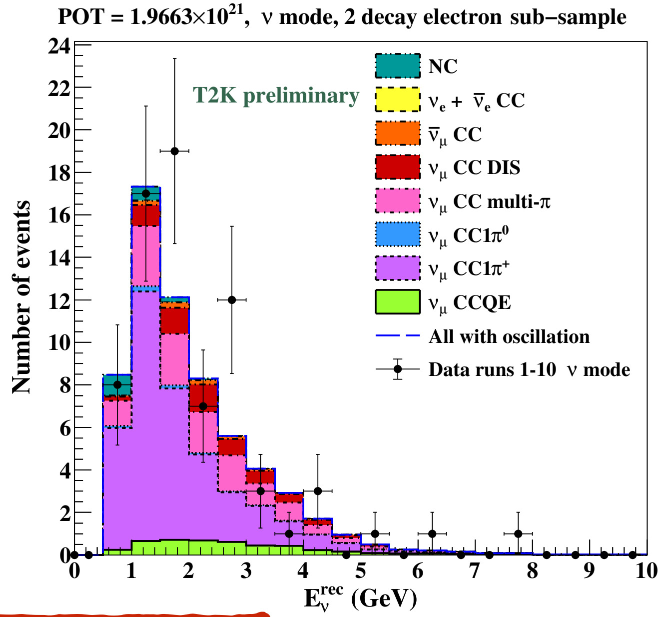
Wrong sign component

6 × 2 anti-neutrino beam mode ND280 samples used in the oscillation analysis

Super-K samples



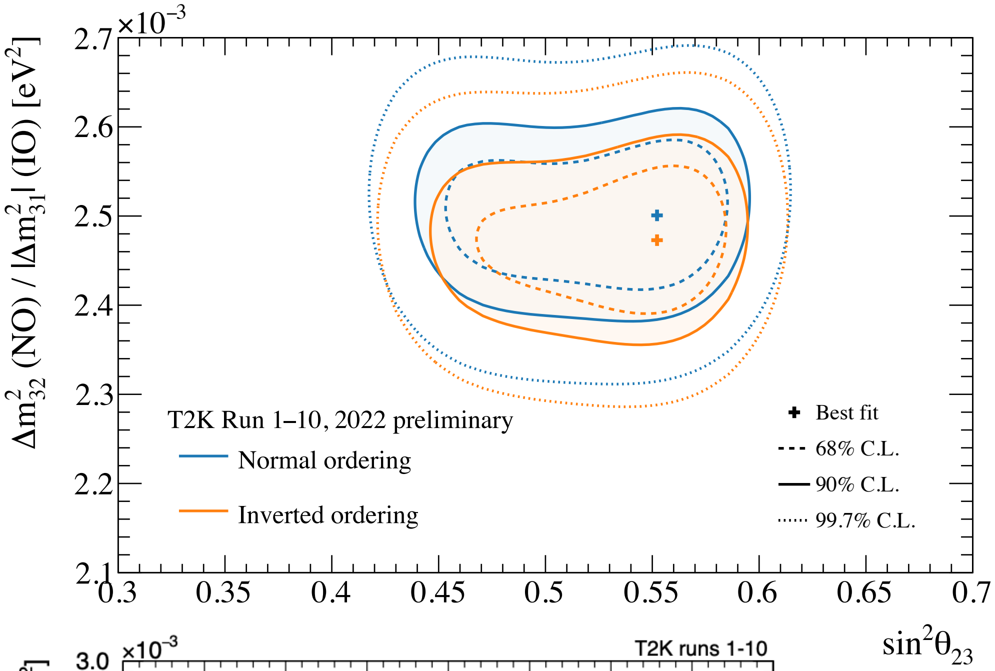


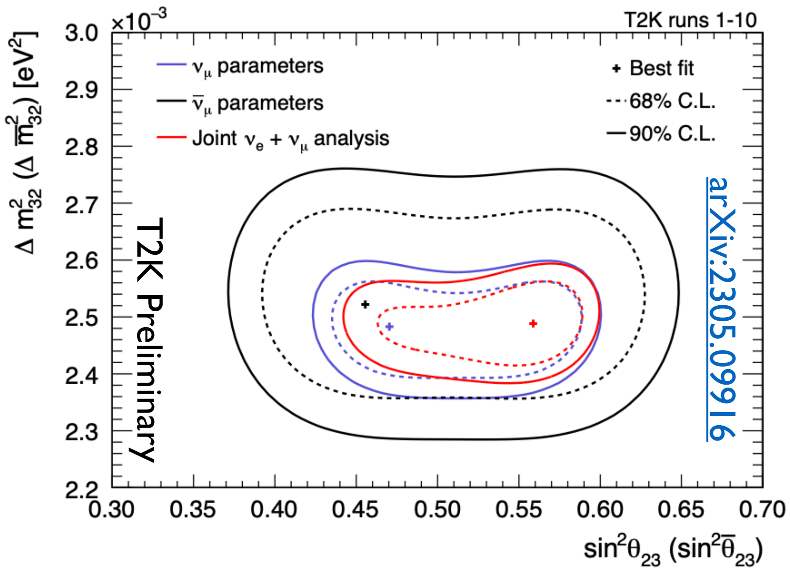


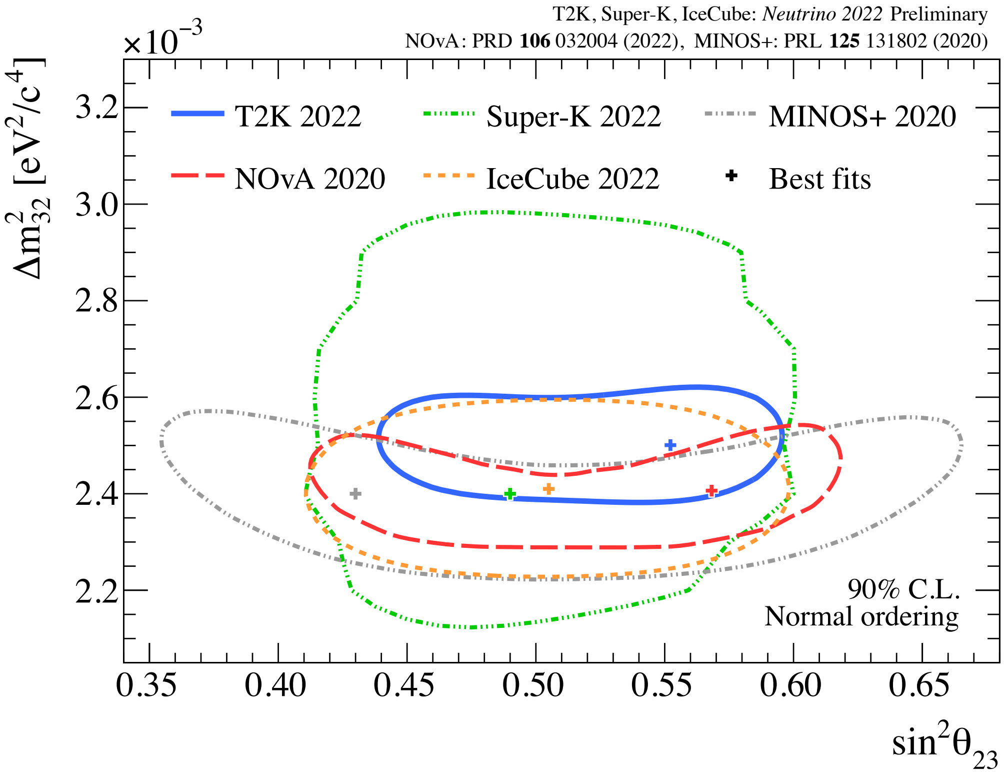
- New "multi-ring" ν_μ CC1π⁺ sample
- Increases μ-like statistics by ~30%
- Small sensitivity to oscillation, tests the robustness of our model

Beam mode	Sample	Description
ν	1Re	One e-like ring, 0 decay electrons
	1Re CC1π⁺	One e-like ring, 1 decay electrons
	1Rμ	One μ-like ring, 0/1 decay electrons
NEW	MRμ CC1π⁺	One μ-like ring, 2 decay electrons/ μ-like ring + π^+-like ring, 1 decay e
$\bar{\nu}$	1Re	One e-like ring, 0 decay electrons
	1Rμ	One μ-like ring, 0/1 decay electrons

Results: θ_{23} vs Δm^2_{23}



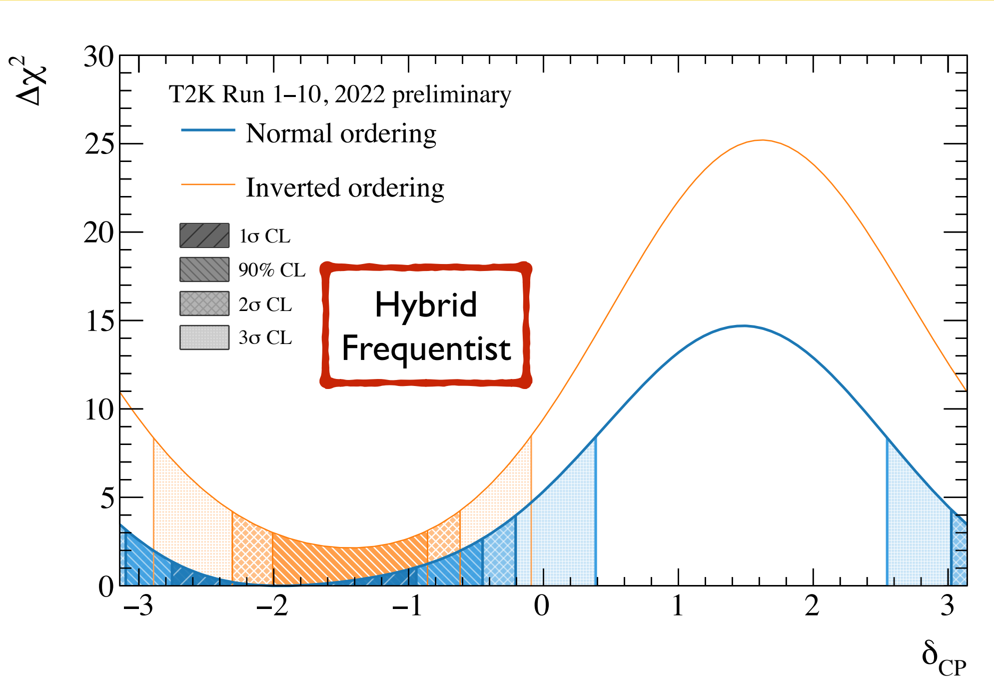


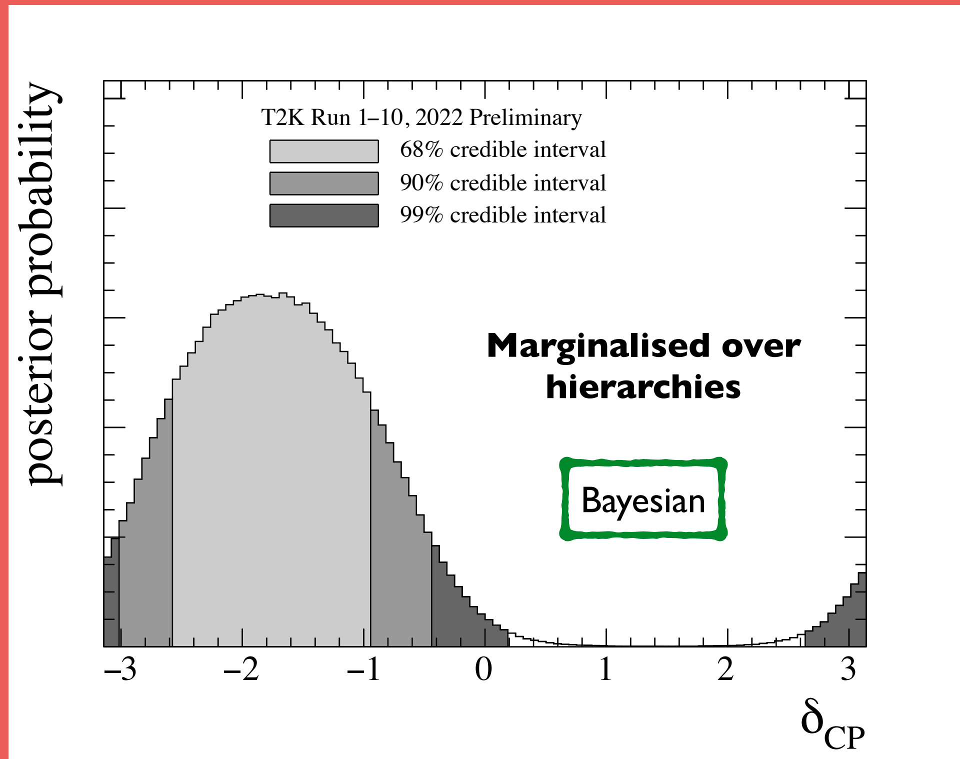


- **World-leading measurement of $\sin^2\theta_{23}$**
- Results continue to be **consistent with maximal mixing/oscillation**
- **No significant differences between ν and $\bar{\nu}$**
- **Reactor constraint applied ($\sin^2 2\theta_{13} = 0.0861 \pm 0.0027$)**

Results: δ_{CP} confidence regions

T2K + Reactor θ_{13} ($\sin^2 2\theta_{13} = 0.0861 \pm 0.0027$)





CP conservation (δ_{CP} = 0,π) excluded at 90% C.L.

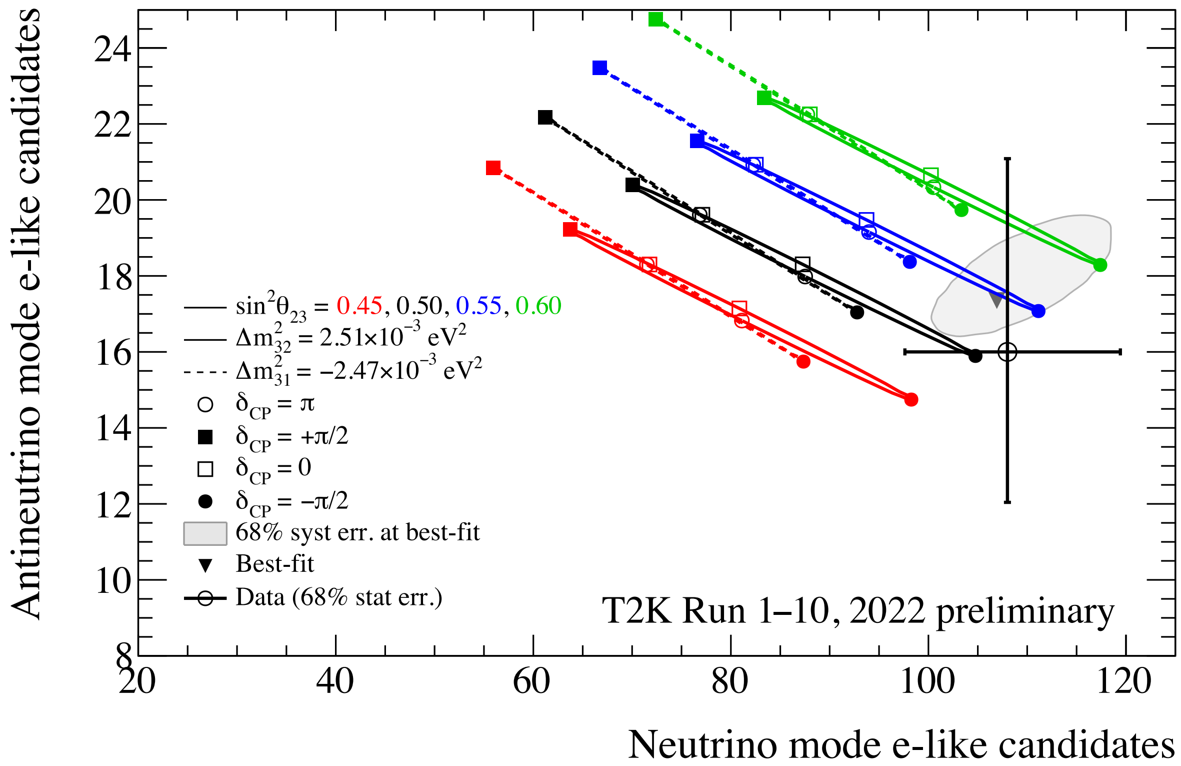
Best fit value near maximal CP violation (-π/2)

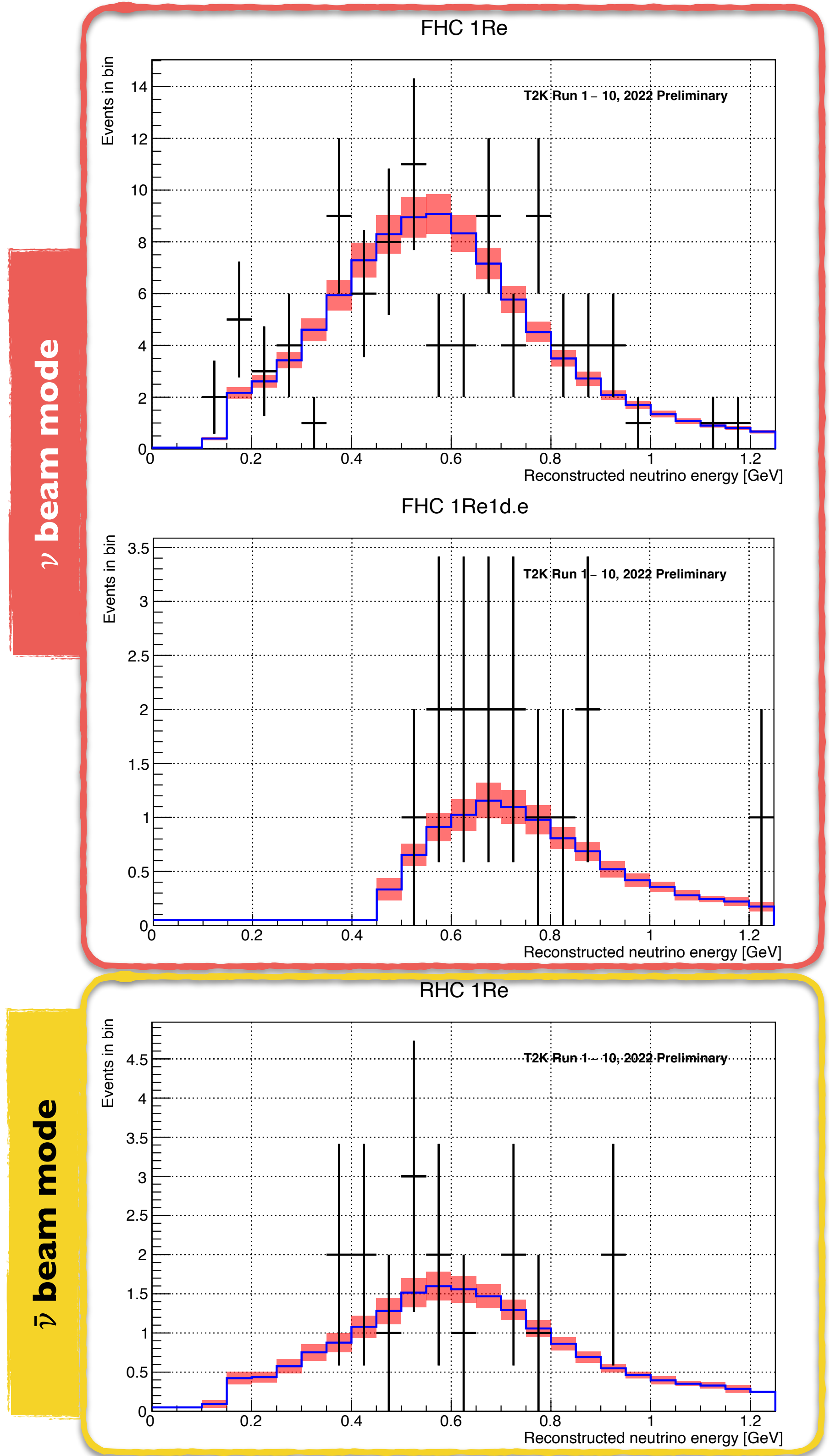
Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.75, -0.94]$	
90%	$[-3.10, -0.45]$	$[-2.01, -0.86]$
2σ	$[-\pi, -0.21] \cup [3.02, \pi]$	$[-2.31, -0.62]$
3σ	$[-\pi, 0.39] \cup [2.55, \pi]$	$[-2.89, -0.09]$

T2K Run 1-10, preliminary

Summary of oscillation results

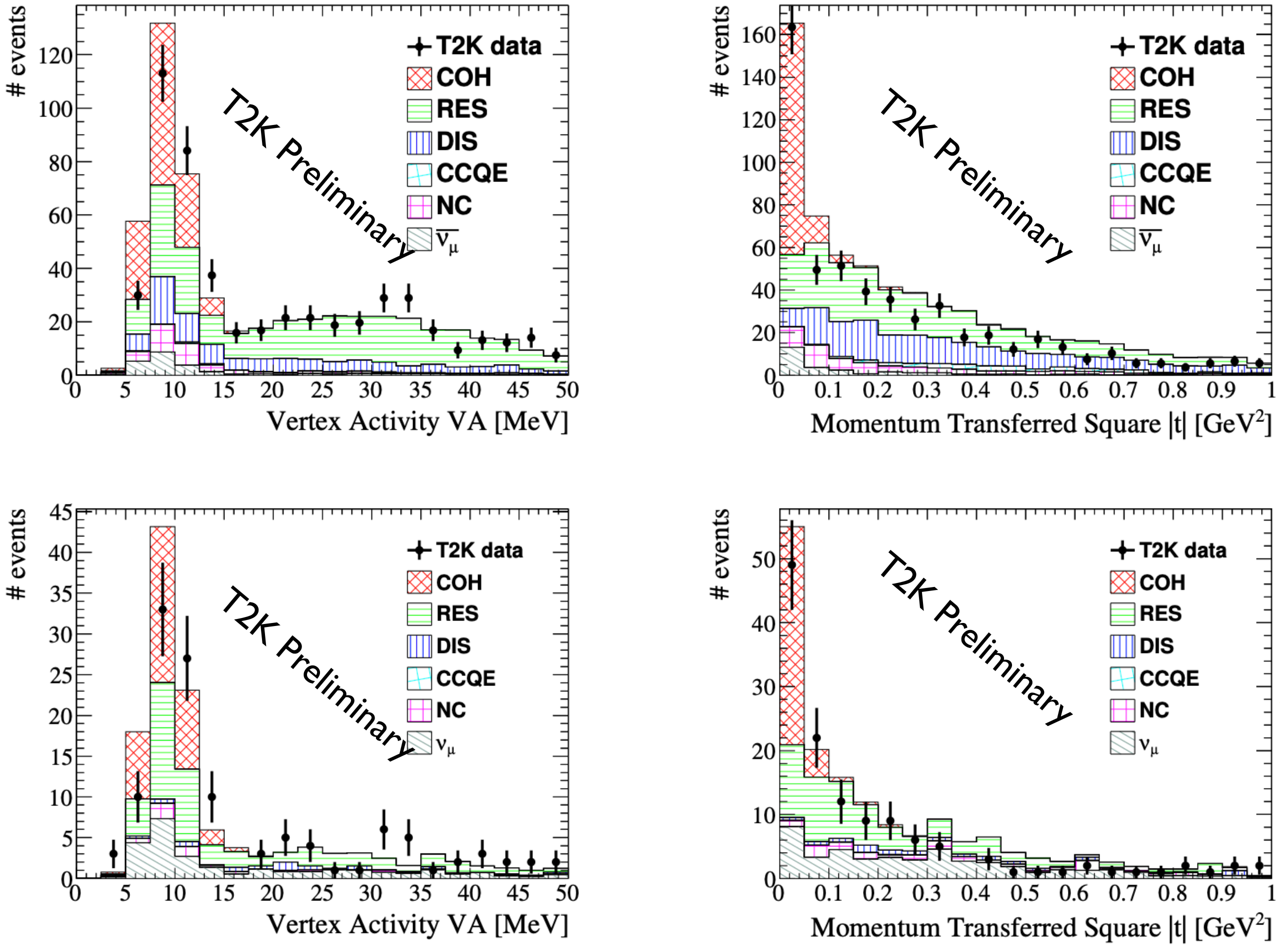
- **Oscillation parameters at the limit**
  - **Maximal mixing in θ_{23}**
  - **Maximal $\nu_e/\bar{\nu}_e$ asymmetry**
- **Consistent w/ PMNS, within stat. +syst. errors**





Latest x-sec results

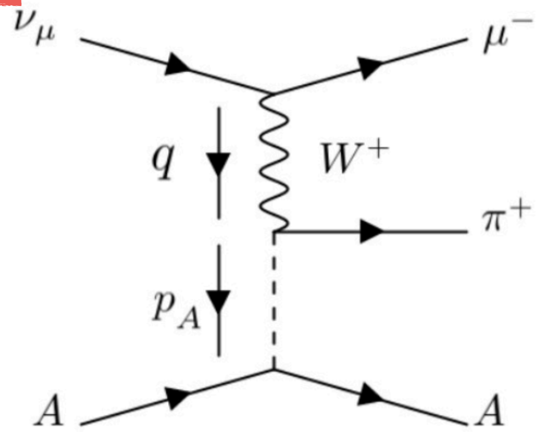
CC Coherent on Carbon @ ND280



arXiv:2308.16606

ν beam mode

$\bar{\nu}$ beam mode

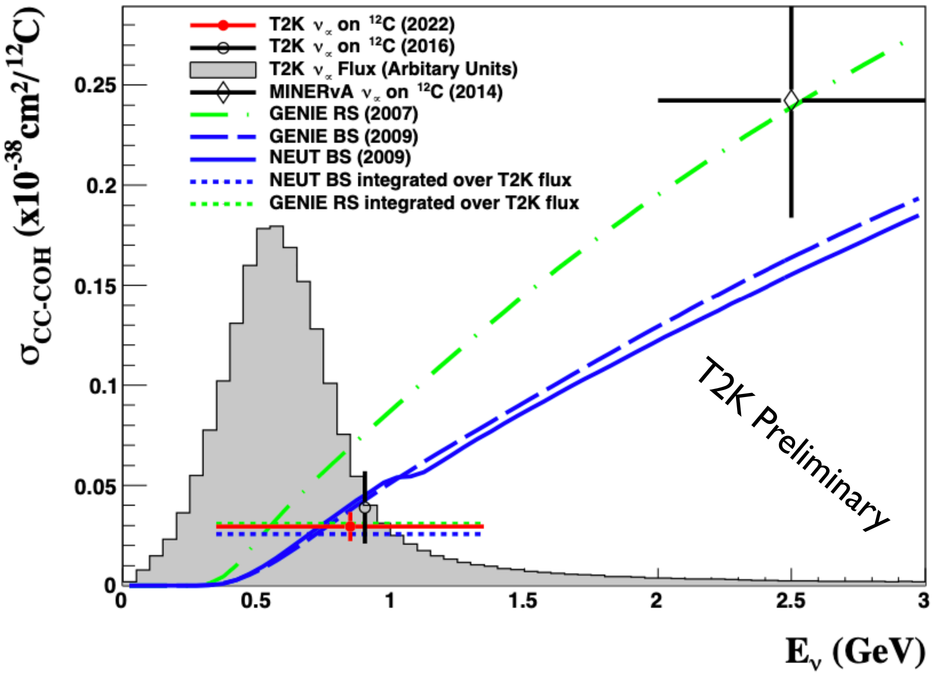


$$|p_A|^2 = |q - p_\pi|^2 = |t|$$

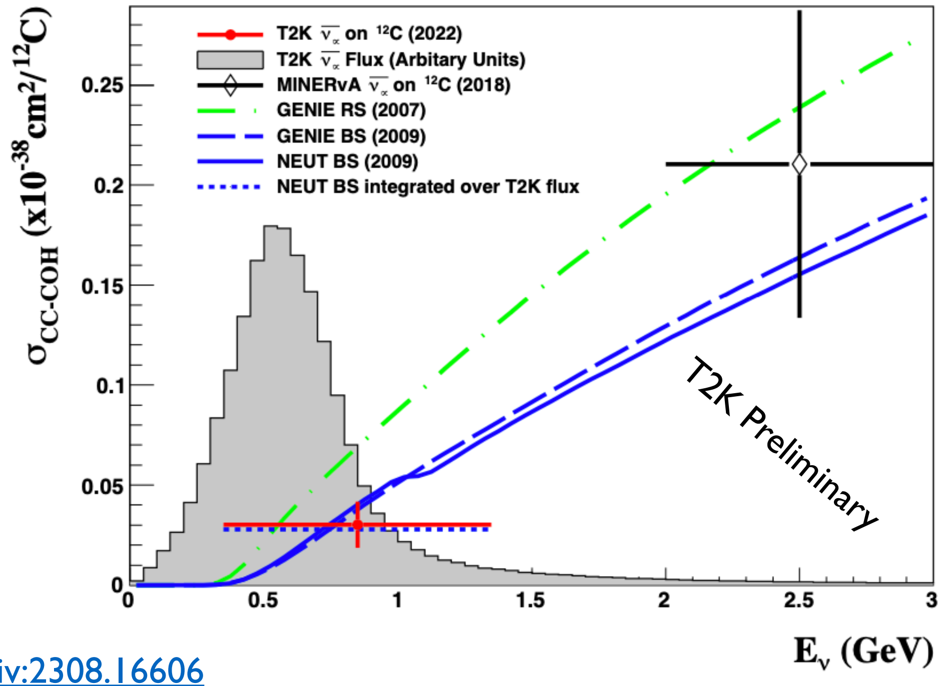
- **Vertex activity = Energy deposited around the vertex**
- **|t| → Momentum transfer from μ and π⁺ kinematics**

CC Coherent on C @ ND280

ν beam mode



$\bar{\nu}$ beam mode

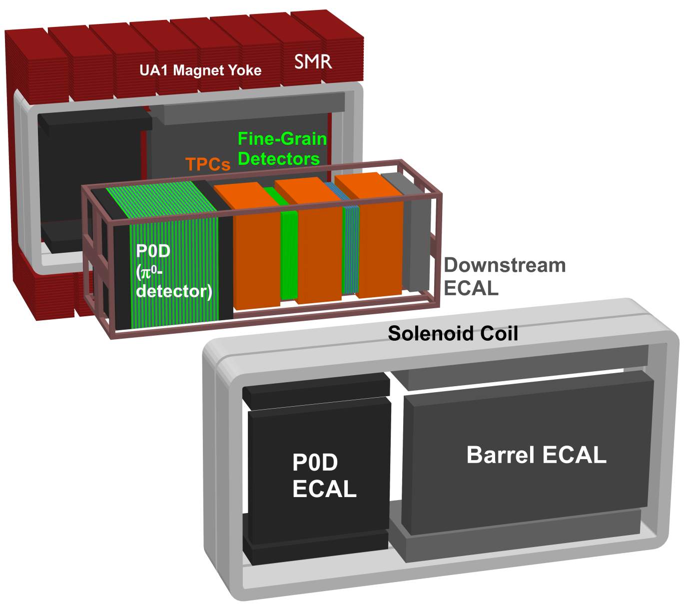


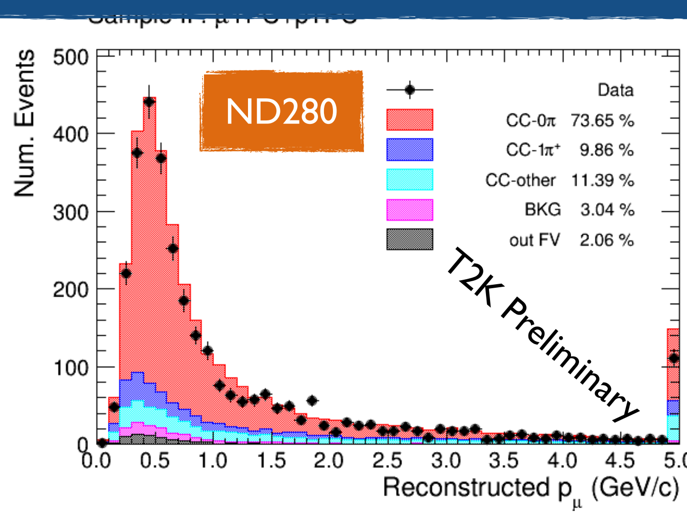
arXiv:2308.16606

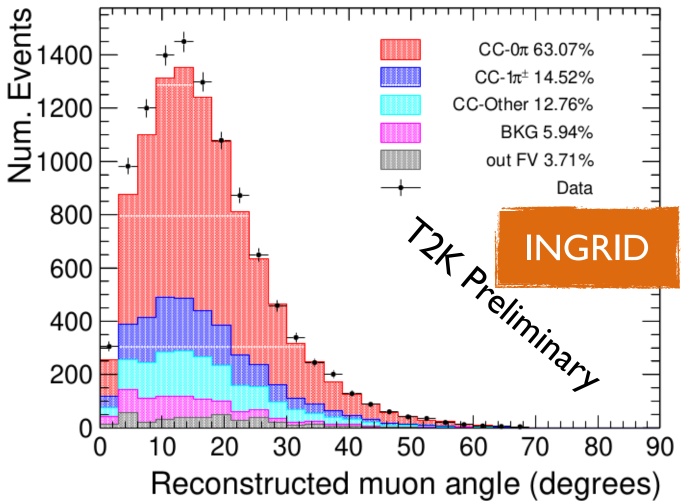
- **Update of 2016 ν_μ results**
- **First measurement of $\bar{\nu}_\mu$ CC Coherent cross-section at ND280**
- **Presently compatible with both Berger Sehgal (NEUT) and Rein Sehgal (GENIE)**

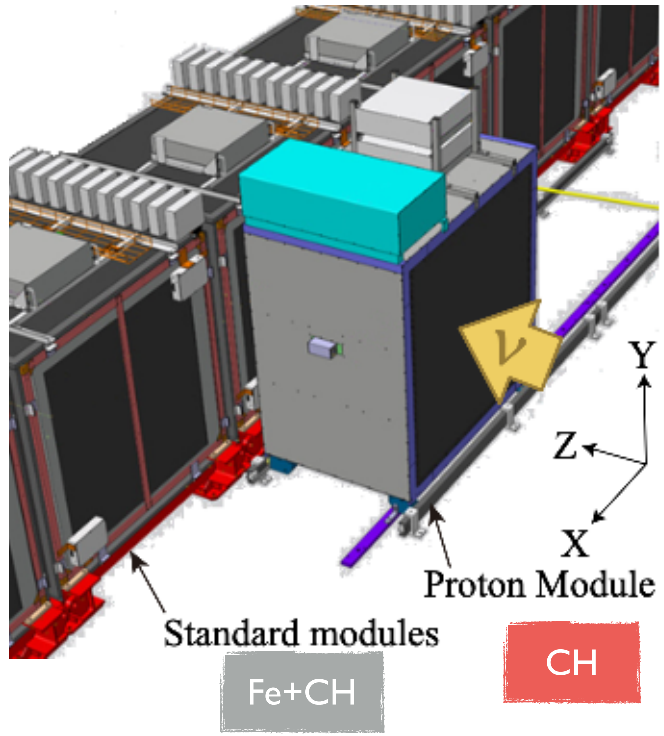
On/off-axis CC0pi cross-section

- Goal of the analysis: measure CC0pi x-sec in two independent detectors (INGRID & ND280) at different fluxes
- INGRID on-axis proton module for cross sections
  - PID via dE/dx & range
  - Momentum by range
- ND280 off-axis (B field)

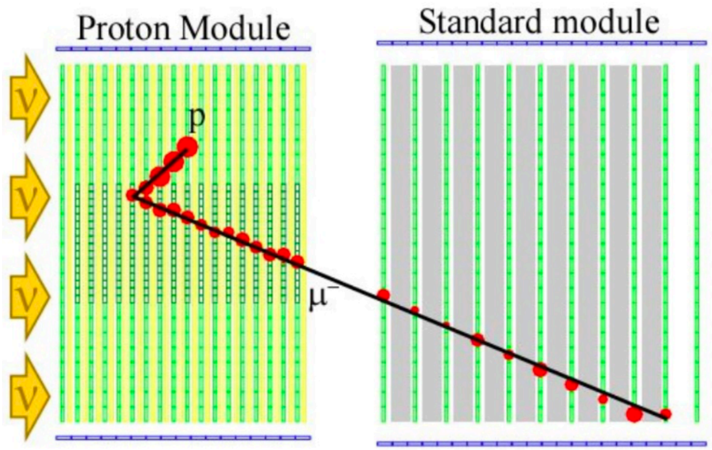






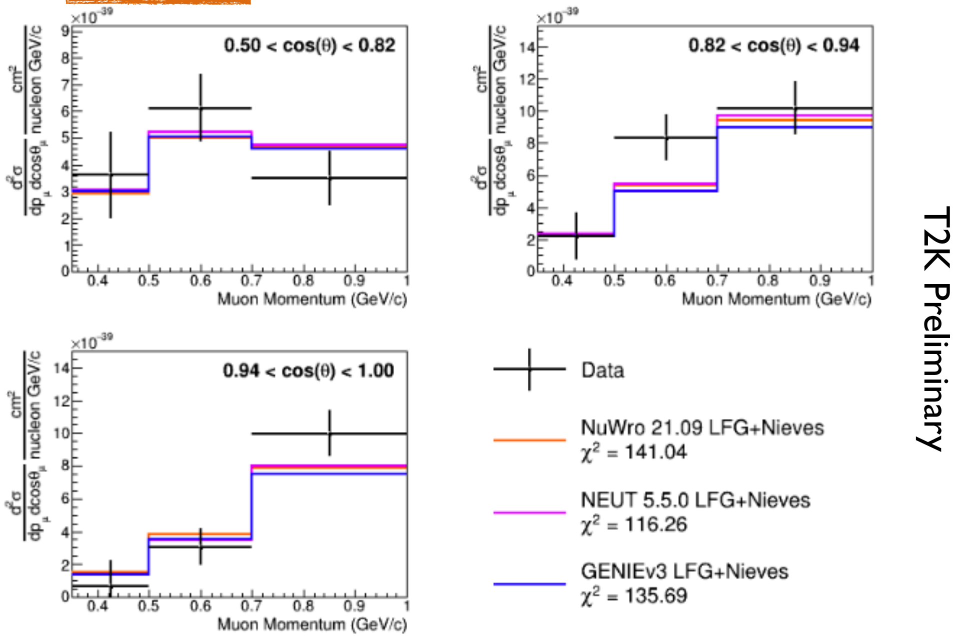


arXiv:2303.14228



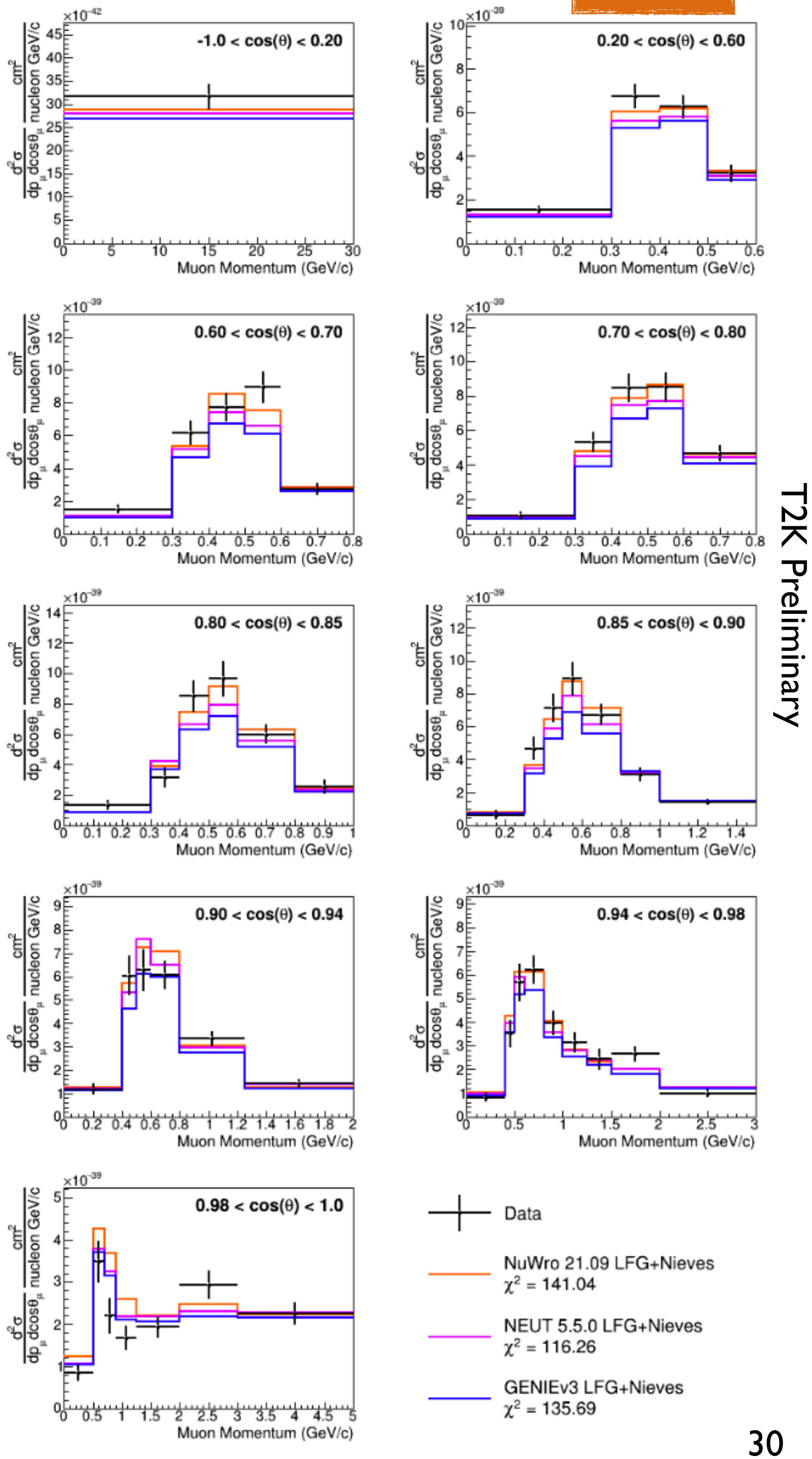
On/off-axis CC0pi cross-section

INGRID



arXiv:2303.14228

ND280



- **Differential cross-section in muon kinematics**
- **70 cross-section bins:**
  - **58 ND280**
  - **12 INGRID**
  - **no single model can describe all bins**
- **Most tension in on-axis, forward-going**
- **Results consistent with previous T2K results**

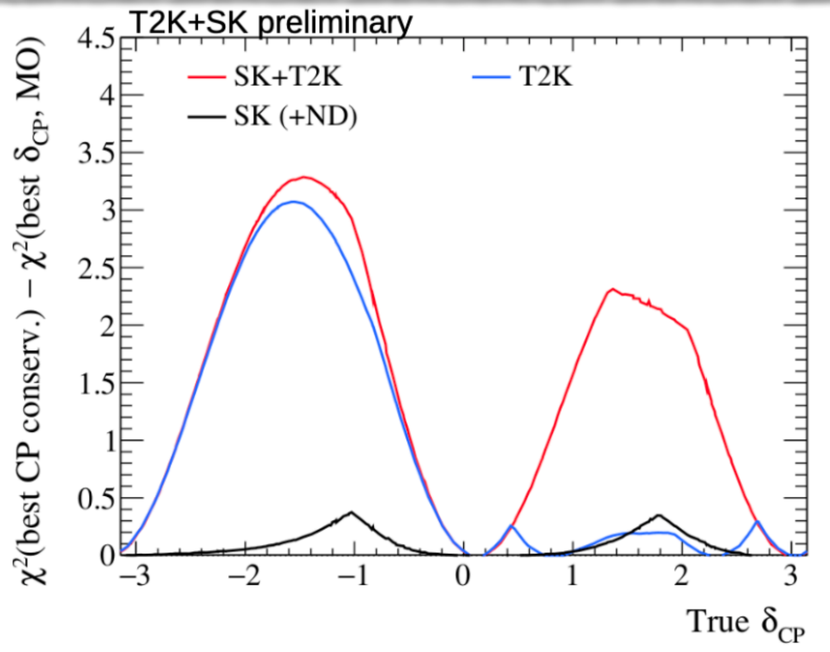
Prospects

T2K-NOνA joint fit

Experimental Property	T2K	NOvA
Proton beam	30 GeV	120 GeV
Baseline	295 km	810 km
Peak nu energy	0.6 GeV	2 GeV
Detection tech	Water Cherenkov	Segmented Liq scin. bars
CP effect	32%	22%
Matter effect	9%	29%

- Combined analysis ongoing
  - Can lead to **increased sensitivity**
- **Degeneracy between δ_{CP} and mass hierarchy can be lifted.**

T2K-SK joint fit



- SK is a common detector for both experiments:
  - **Strong correlations in detector systematics**, and also a common neutrino interaction model.
  - δ_{CP} sensitivity mainly driven by T2K.
- SK covers large range of neutrino energies and baselines, hence **better mass hierarchy sensitivity**.
- See Aoi Eguchi talk

Furthermore…

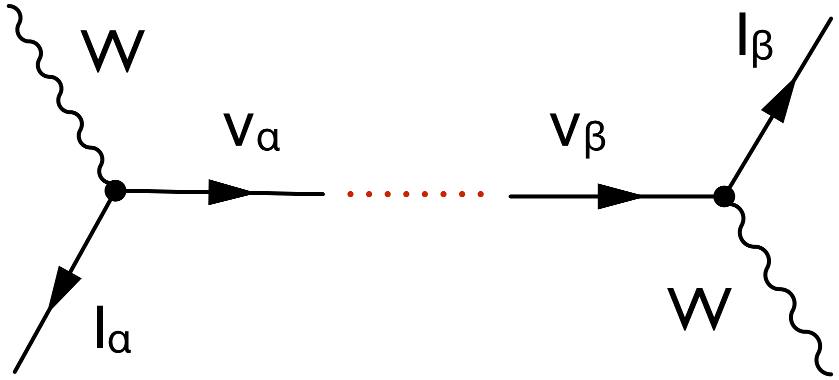
- **J-PARC accelerator upgrade**
- **Near detector upgrade** (see Xingyu Zhao talk)
- New data with **Gd loaded SK** which will enable use of neutron tagging information.
- New SK multi-ring samples that can improve our sensitivities to oscillation parameters.

Conclusions

- **Presented the latest T2K results from 2022 analysis**
- **Several improvements in the oscillation analysis**
  - New flux tuning with T2K replica target
  - New cross-section model constrained with ND280 data
  - New ND280 and Super-K samples
- **Data continue to prefer maximal θ_{23} mixing, δ_{CP} ~-π/2 and NH**
  - CP conserving values are excluded at 90% C.L.
  - Mild preferences for normal ordering and upper octant
- **New x-sec results from ND280:**
  - New results on CC0π and CC Coherent x-sec
  - A lot of x-sec measurements ongoing:
    - $\nu_\mu CC1K^+$ on CH @ ND280, CC0π on water and CH @ WAGASCI, NC1$\pi^{0/+}$ on CH/H_2O @ ND280, (anti-)$\nu_\mu CC1\pi^{+(-)}$ on CH/H_2O @ ND280, …
- **Prospects:**
  - T2K-SK joint analysis to improve sensitivity to δ_{CP}
  - T2K-NOνA joint analysis to disentangle degeneracy between δ_{CP} and mass hierarchy
  - Near detector and beam upgrade to enter in the precision era of neutrino oscillation.

Backup

Neutrino oscillations



Neutrinos produced in weak processes (ν_α) are linear combinations of mass eigenstates (ν_i)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

where **U** is the **Pontecorvo-Maki-Nakagawa-Sakata (PMNS)** matr

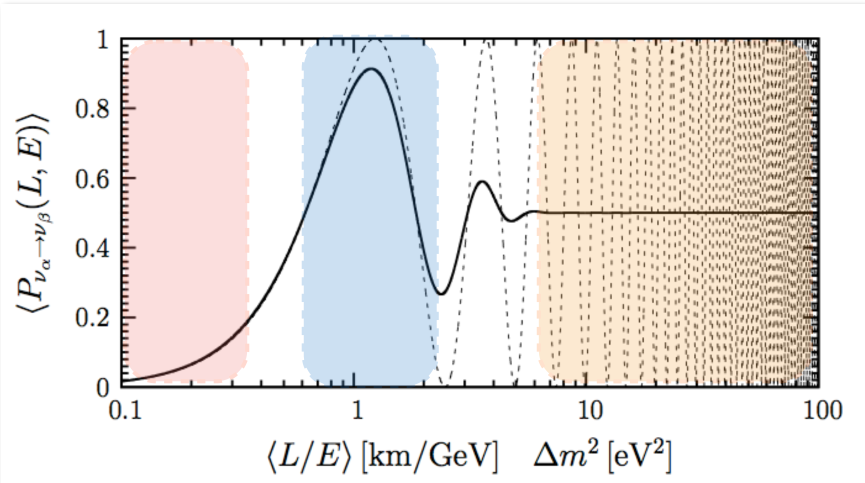
Time evolution: flavor content "oscillates" in L(distance)/E(neutrino)

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2\left[1.27\Delta m^2_{ij}(L/E)\right] + 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin\left[2.54\Delta m^2_{ij}(L/E)\right]$$

oscillation amplitude

oscillation frequency

Parameters controlled by experiments



L/E << Δm^2 no time for the oscillation to develop

L/E >> Δm^2 only average oscillation probability can be measured

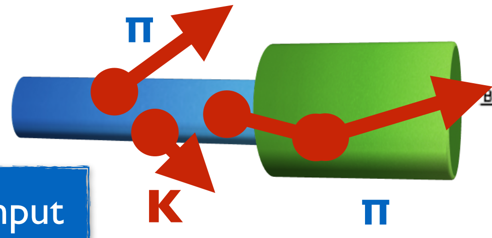
L/E ≈ Δm^2 best sensitivity to oscillation

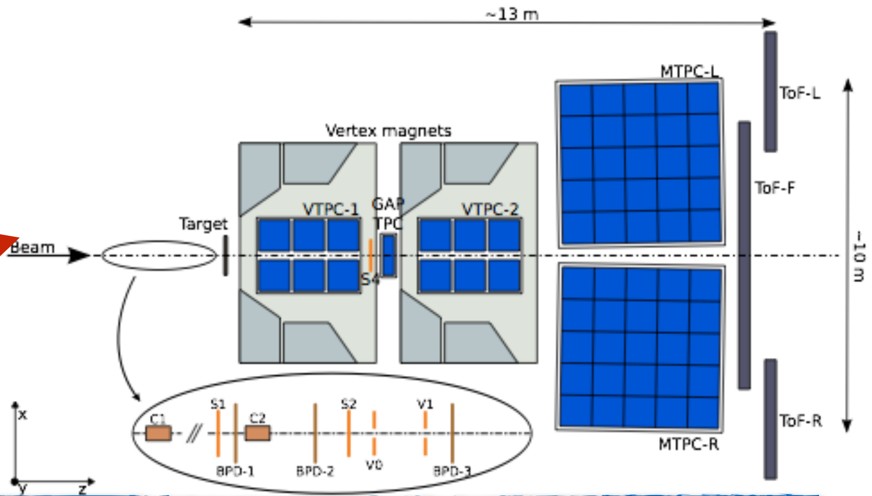
The neutrino beam: flux predictions

- Fluxes are predicted from a data-driven simulation → **NA61/SHINE experiment** measures hadron production cross sections using a **T2K replica target**

Flux error reduction from ~25% to less than 10%

Proton beam | Graphite target | Horn

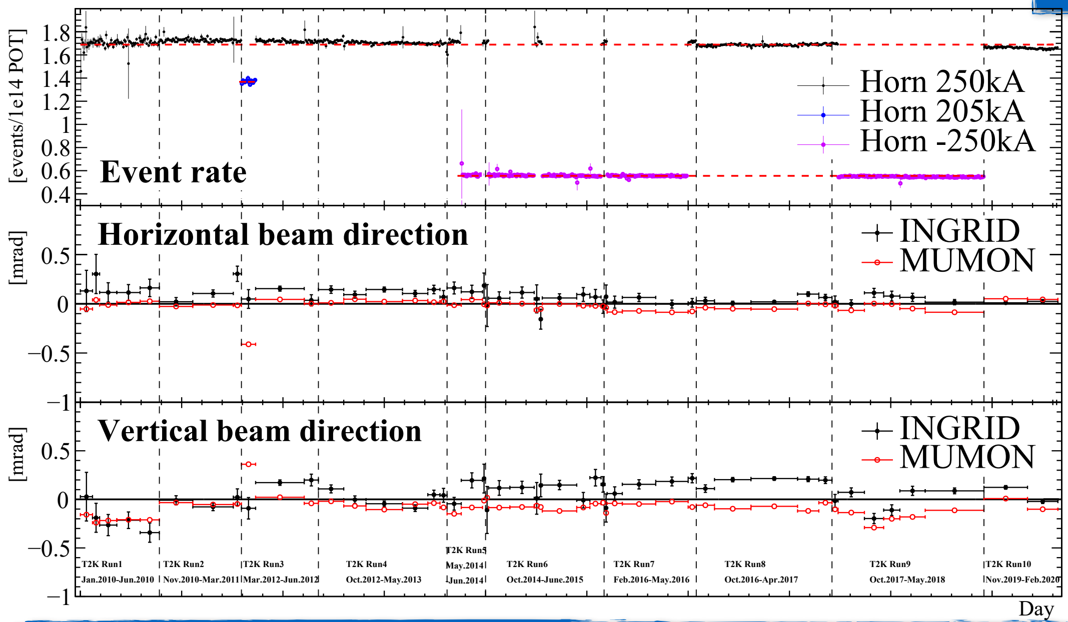




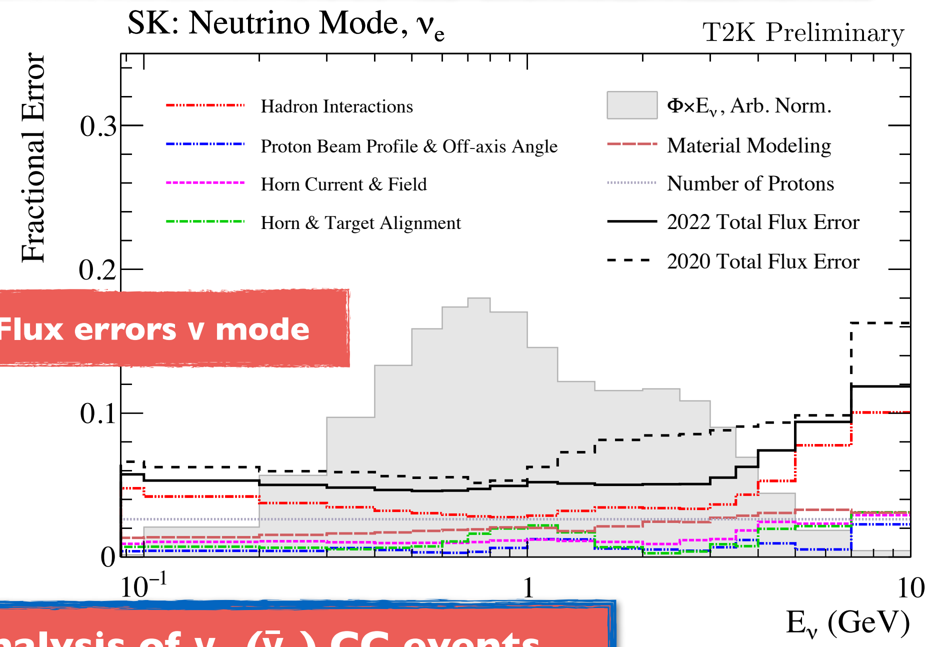
- Beam alignment monitoring provides input to estimations of beam systematics

- INGRID detector provides high-statistics monitoring of the beam intensity, direction, profile and stability

ν daily event rate



Flux errors ν mode

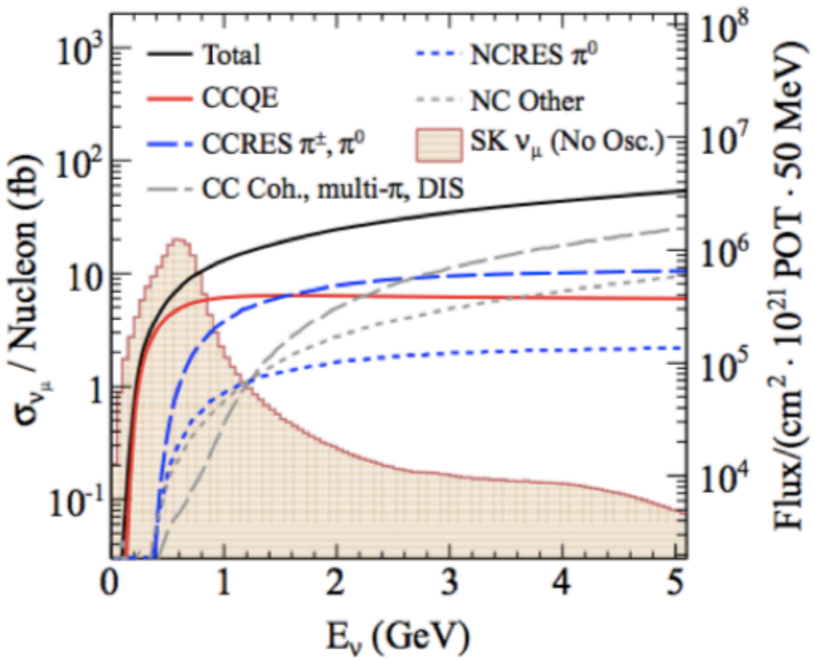


Flux errors are further constrained with the ND280 analysis of ν_μ ($\bar{\nu}_\mu$) CC events

Neutrino cross sections at T2K energies

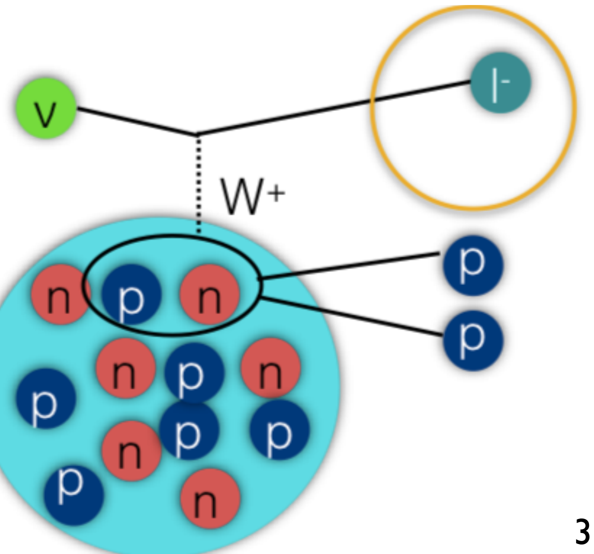
- At T2K energies the favoured interactions are **CCQE**
  - Other neutrino interactions with production of **pions** in the final state are important as well
  - **Nuclear effects** can mimic a CCQE interaction

- **Mimic CCQE interactions:**
  - Neutrino scatters on a correlated pair of nucleons (called multi-nucleon or 2 particle-2 hole, **2p-2h**)
  - Neutrino scatter produces a pion, which is re-absorbed in the nucleus
  - Neutrino scatter produces a pion absorbed by the detector

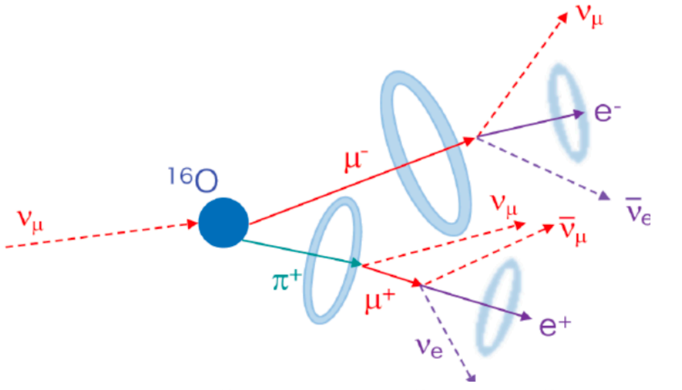


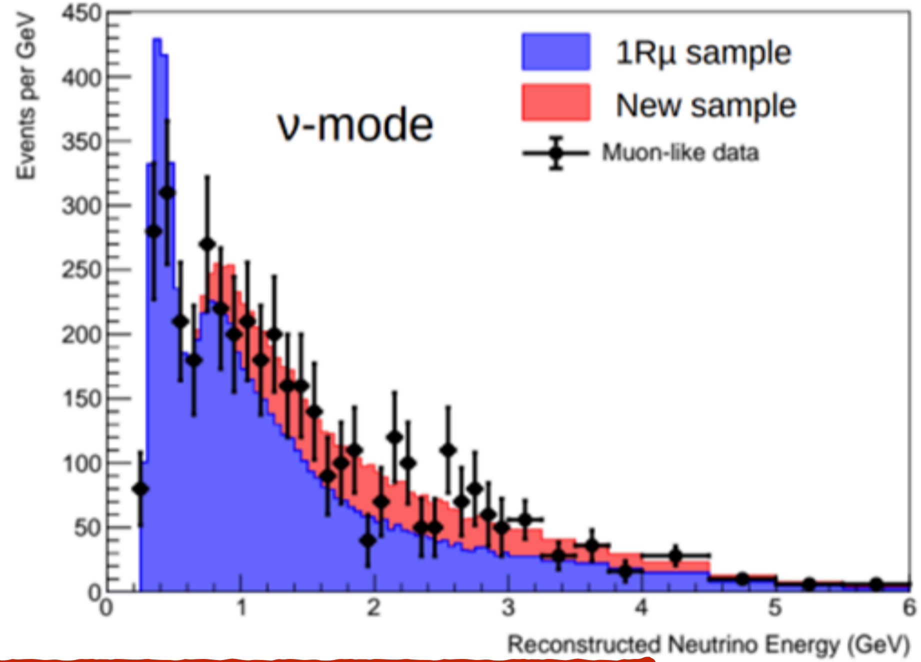
Improvements of neutrino interaction model in NEUT:

- **Improved pion production model** with tuning to data on hydrogen and deuterium
- **Inclusion of a model for multi-nucleon scattering processes**: Valencia 2p-2h model (Phys. Rev. C83 (2011) 045501)
- Improved the CCQE model by including the effect of **long-range correlations in the nucleus** (calculation technique called random phase approximation, **RPA**)



Super-K samples

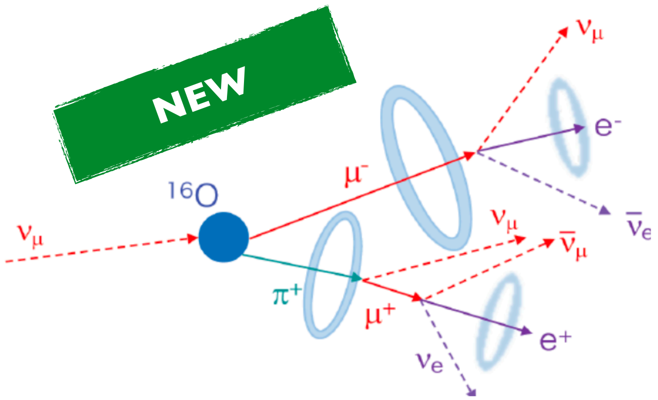


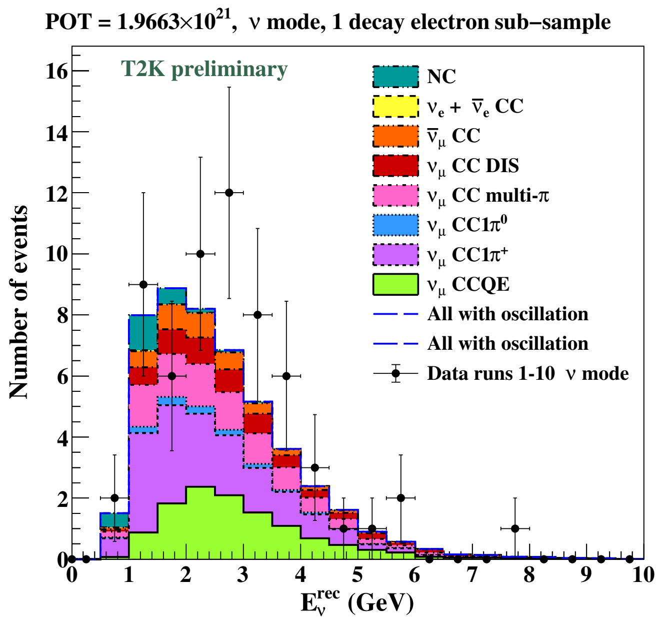


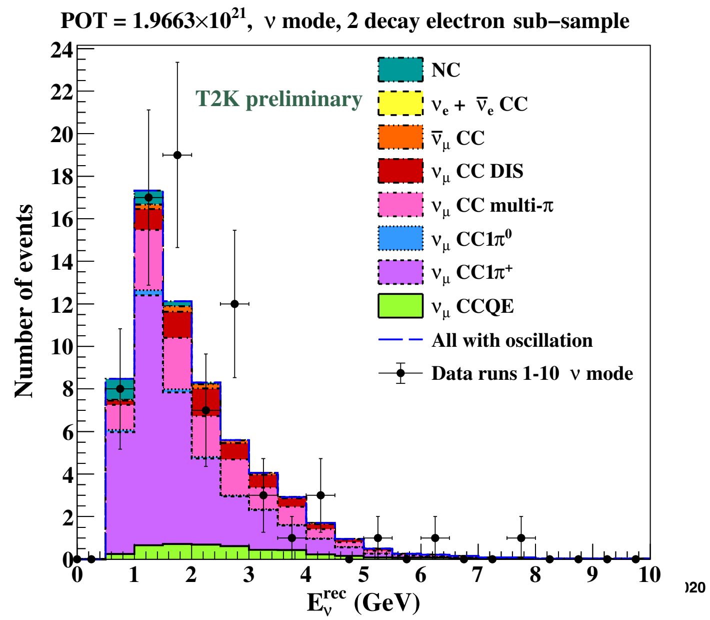
- New "multi-ring" ν_μ CC1π+ sample
- Increases μ-like statistics by ~30%
- Small sensitivity to oscillation, tests the robustness of our model

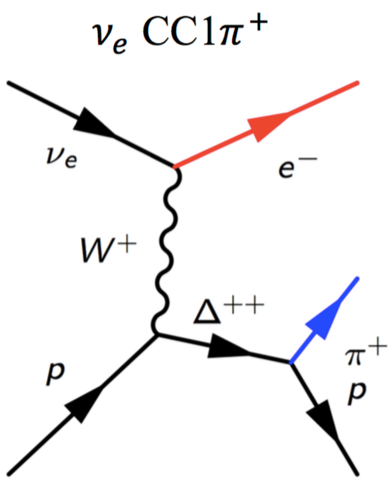
Beam mode	Sample	Description
ν	1Re	One e-like ring, 0 decay electrons
	1Re CC1π+	One e-like ring, 1 decay electrons
	1Rμ	One μ-like ring, 0/1 decay electrons
NEW	MRμ CC1π+	One μ-like ring, 2 decay electrons/ μ-like ring + π+-like ring, 1 decay e
$\bar{\nu}$	1Re	One e-like ring, 0 decay electrons
	1Rμ	One μ-like ring, 0/1 decay electrons

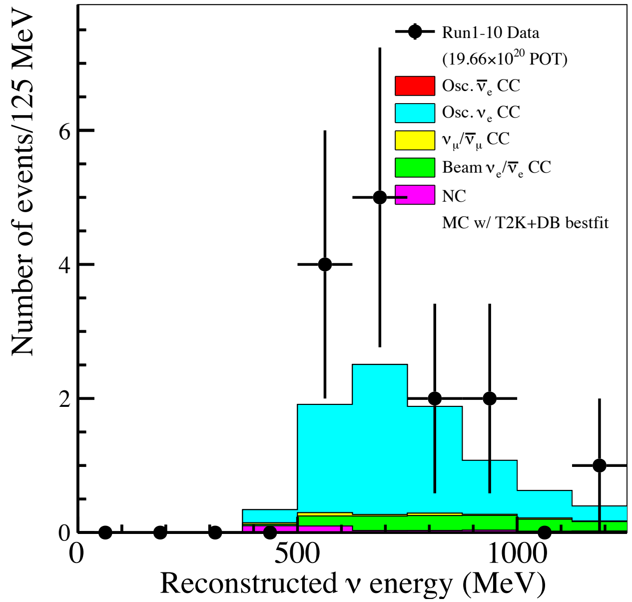
Pion samples @ SK

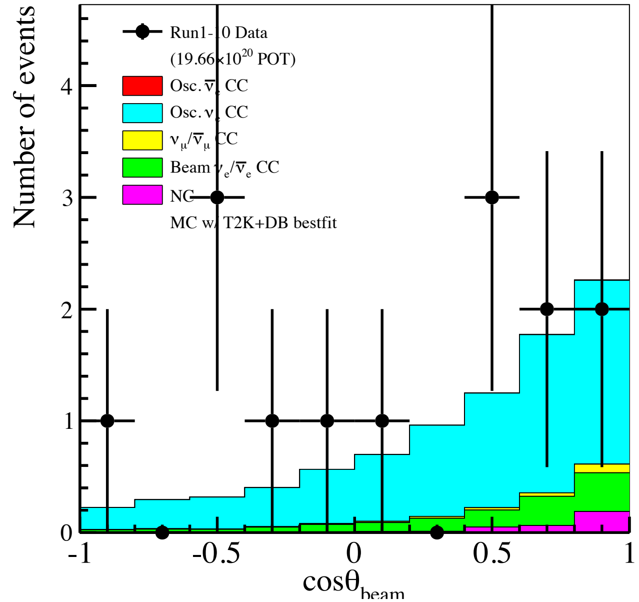








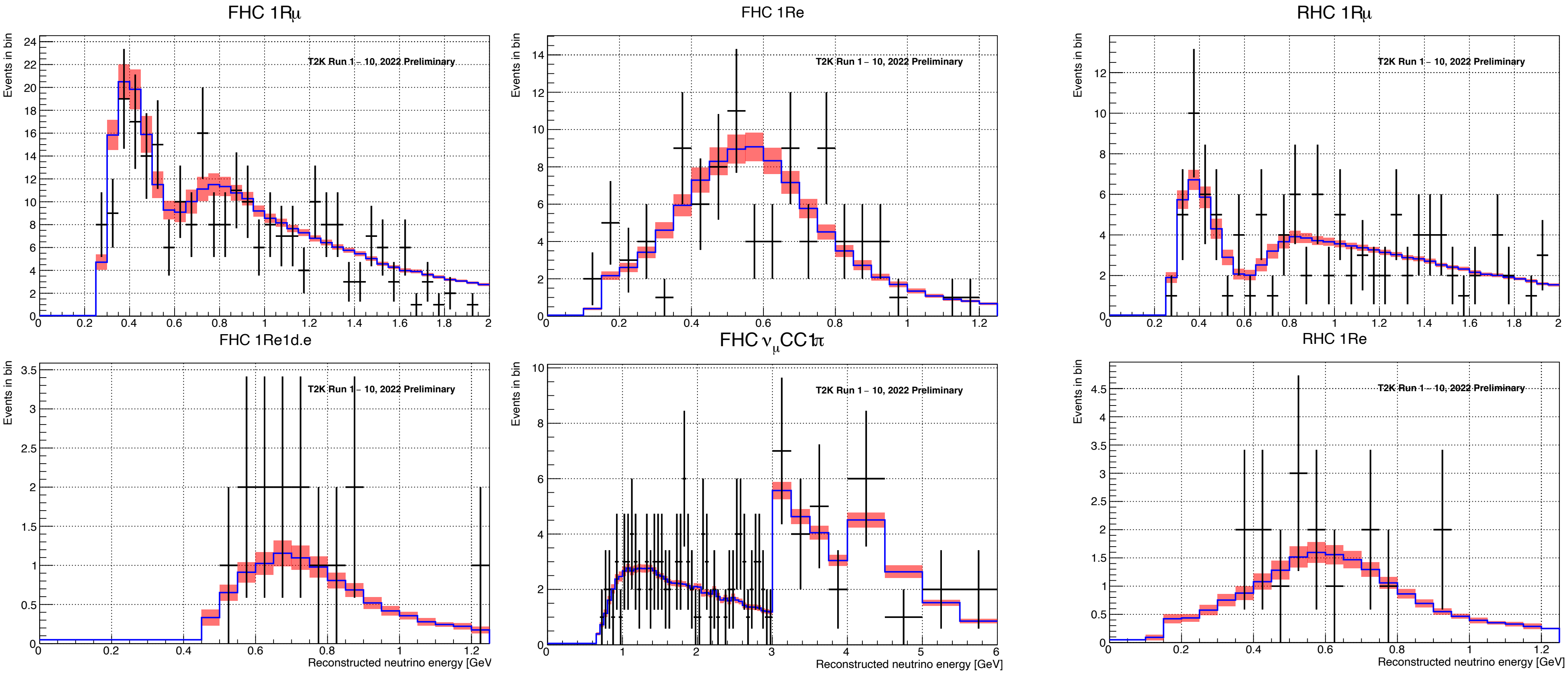




$$E_{rec}^{\nu_\mu\ CC\Delta^{++}} = \frac{2m_p E_\mu + m_{\Delta^{++}}^2 - m_p^2 - m_\mu^2}{2(m_p - E_\mu + |\mathbf{p}_\mu|\cos\theta_\mu)}$$

Fitted spectra at Super-Kamiokande

ν beam mode | **ν̄ beam mode**



	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	$\delta_{CP}=-2.18$	Data
FHC 1Rμ	358.669	358.011	358.63	359.405	359.083	318
RHC 1Rμ	139.427	139.094	139.429	139.788	139.63	137
FHC 1Re	99.0567	83.5624	68.6139	84.1084	96.4746	94
RHC 1Re	17.0154	19.3474	21.4265	19.0946	17.3399	16
FHC 1R ν_e CC1π^+	10.8521	9.44959	7.70161	9.10421	10.4699	14
FHC MR ν_μ CC1π^+	118.527	118.017	118.501	119.02	118.813	134
FHC 1Rμ ($E_{rec}<1.2\,\mathrm{GeV}$)	217.808	217.493	217.78	218.21	218.029	191
RHC 1Rμ ($E_{rec}<1.2\,\mathrm{GeV}$)	71.9451	71.7674	71.9474	72.1506	72.0591	71

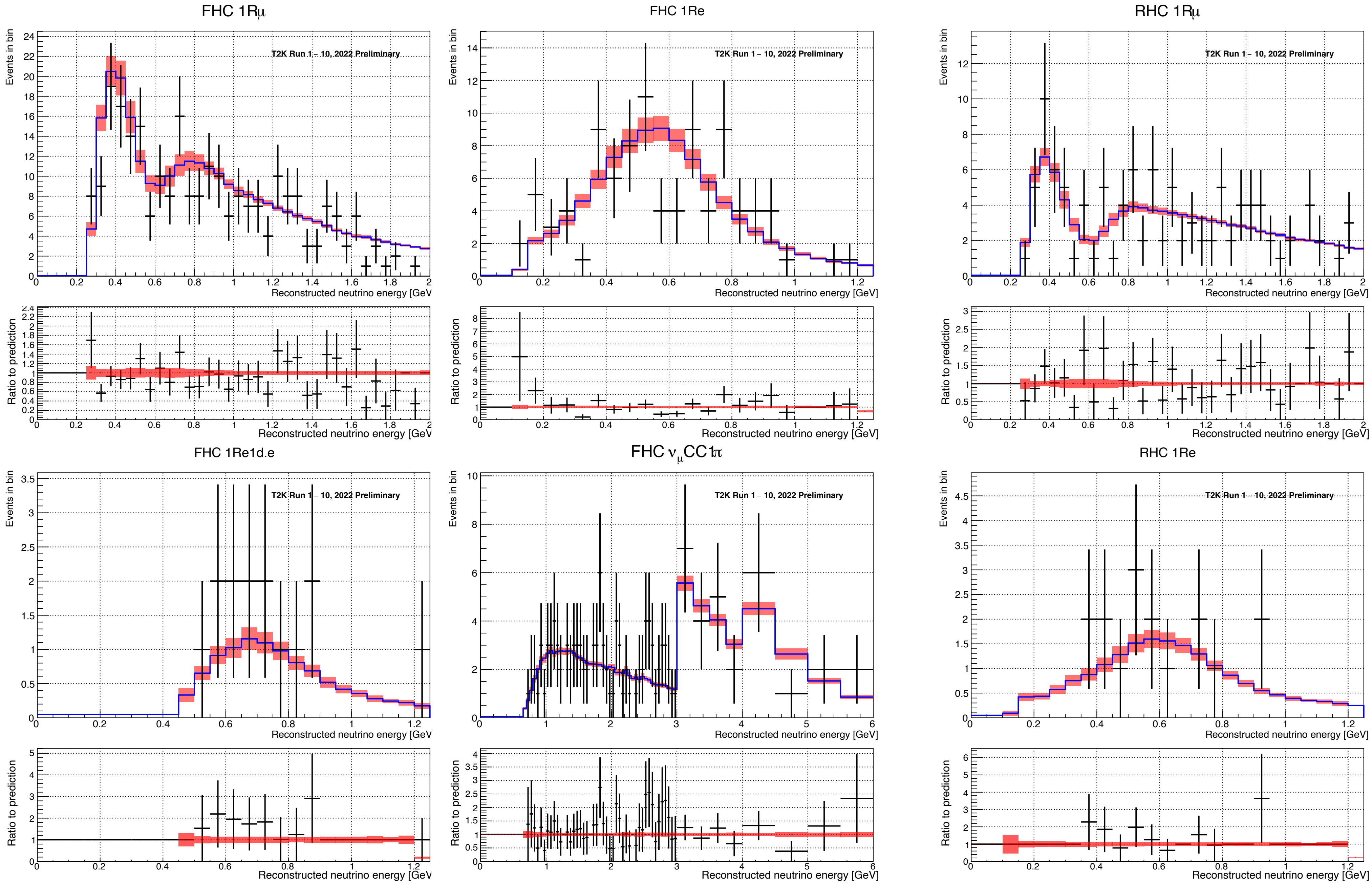
T2K Run 1-10, preliminary

- **Oscillation and systematic parameters are shared between the 6 samples**
- **Fit simultaneously the 6 samples to maximize the sensitivity to the oscillation parameters**

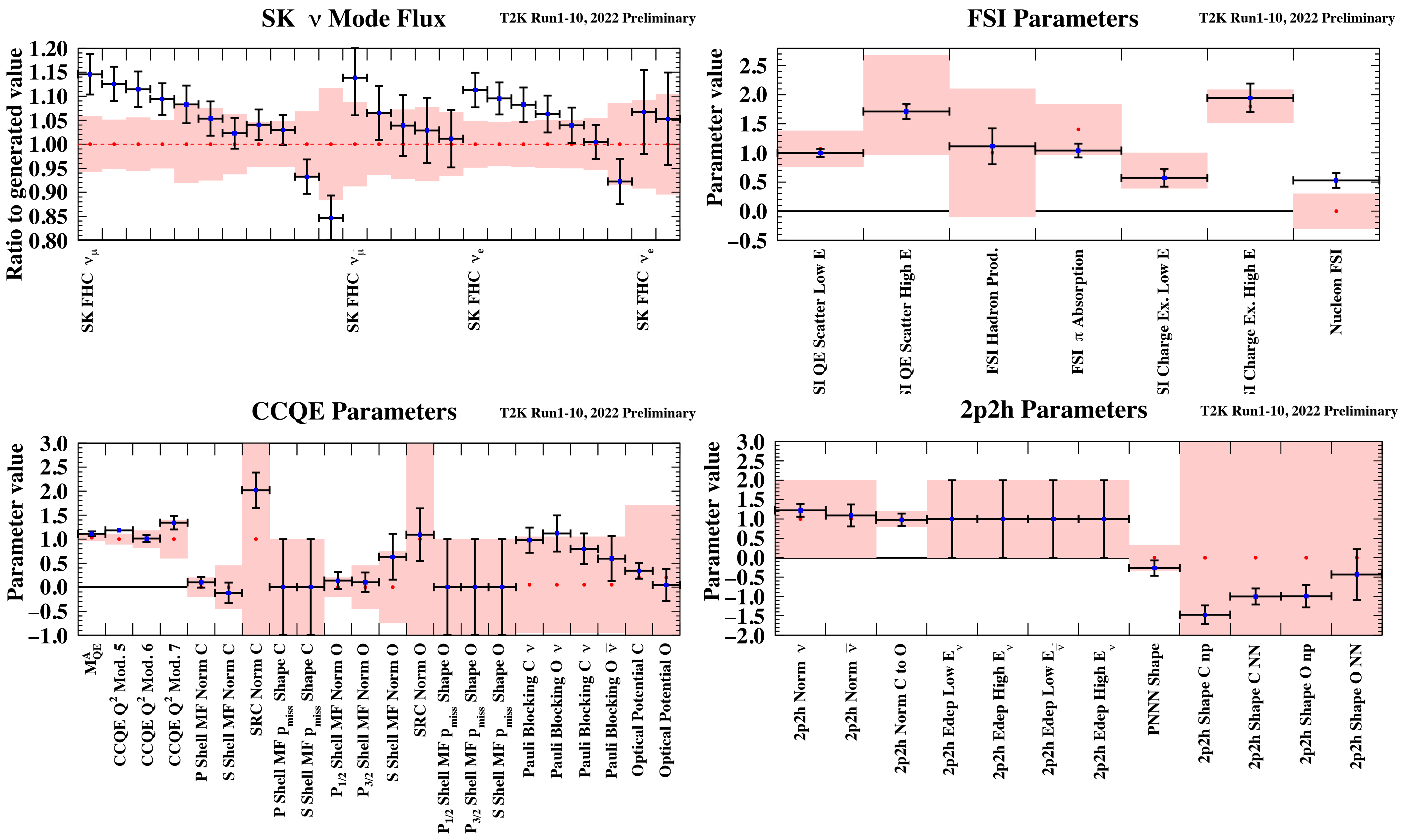
Fitted spectra at Super-Kamiokande

ν beam mode

ν̄ beam mode

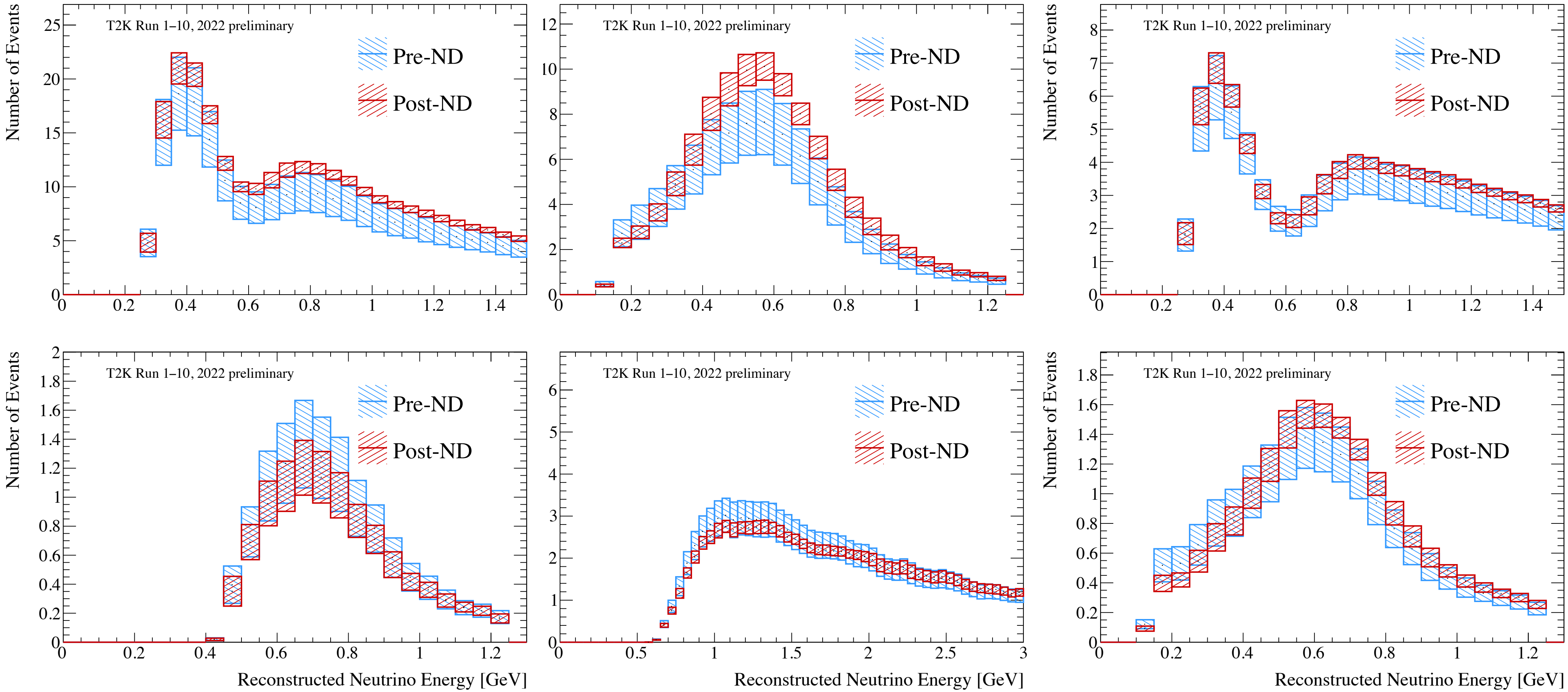


ND280 best fit nuisance parameters



ND280 constraints for Super-Kamiokande

ν beam mode | **ν̄ beam mode**



Before ND280 fit

Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	5.0	4.6	5.2	4.9	4.6	5.1	4.5
Cross-section (all)	15.8	13.6	10.6	16.3	13.1	14.7	10.5
SK+SI+PN	2.6	2.2	4.0	3.1	3.9	13.6	1.3
Total All	16.7	14.6	12.5	17.3	14.4	20.9	11.6

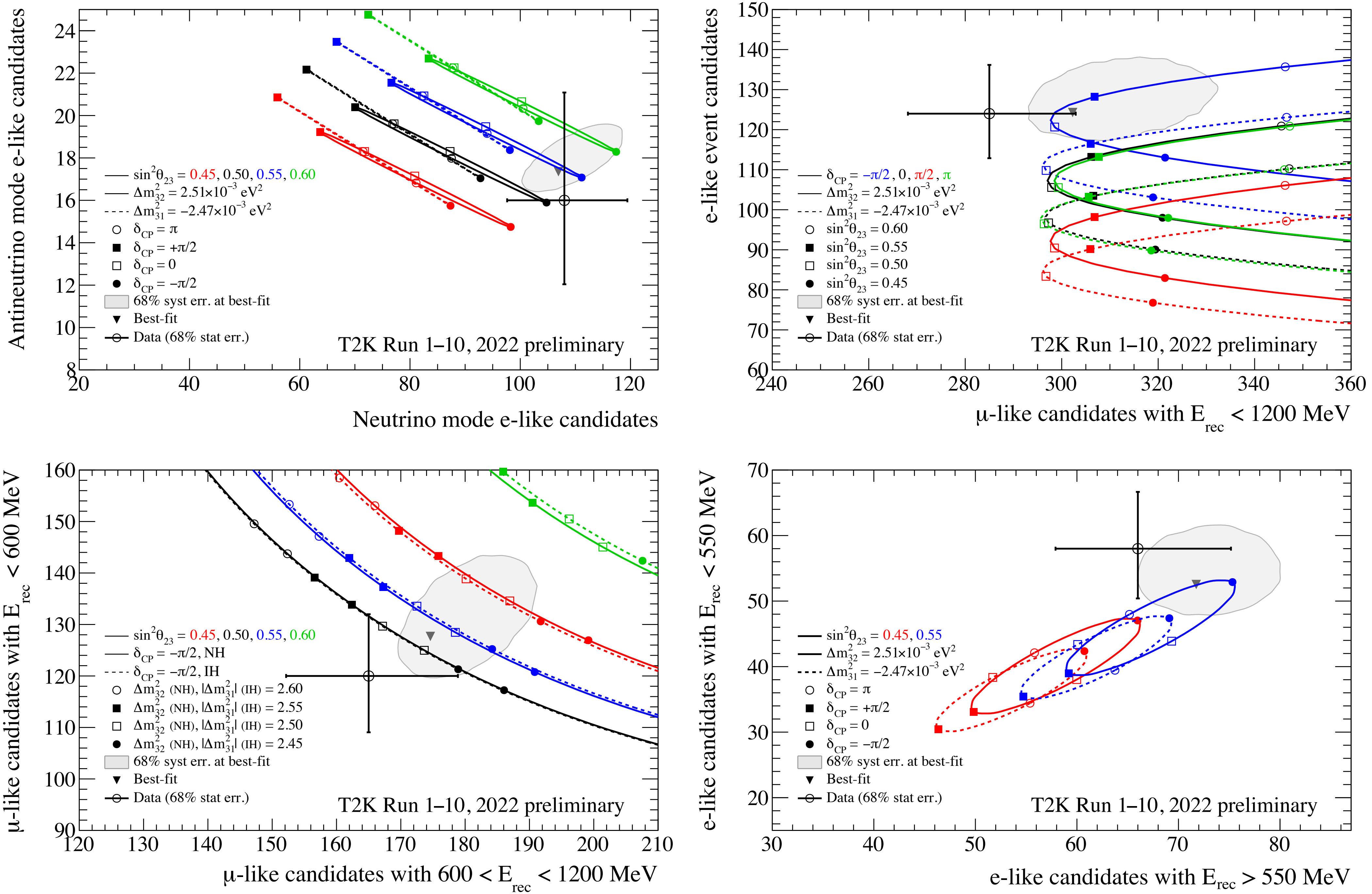
T2K Run 1-10, preliminary

After ND280 fit

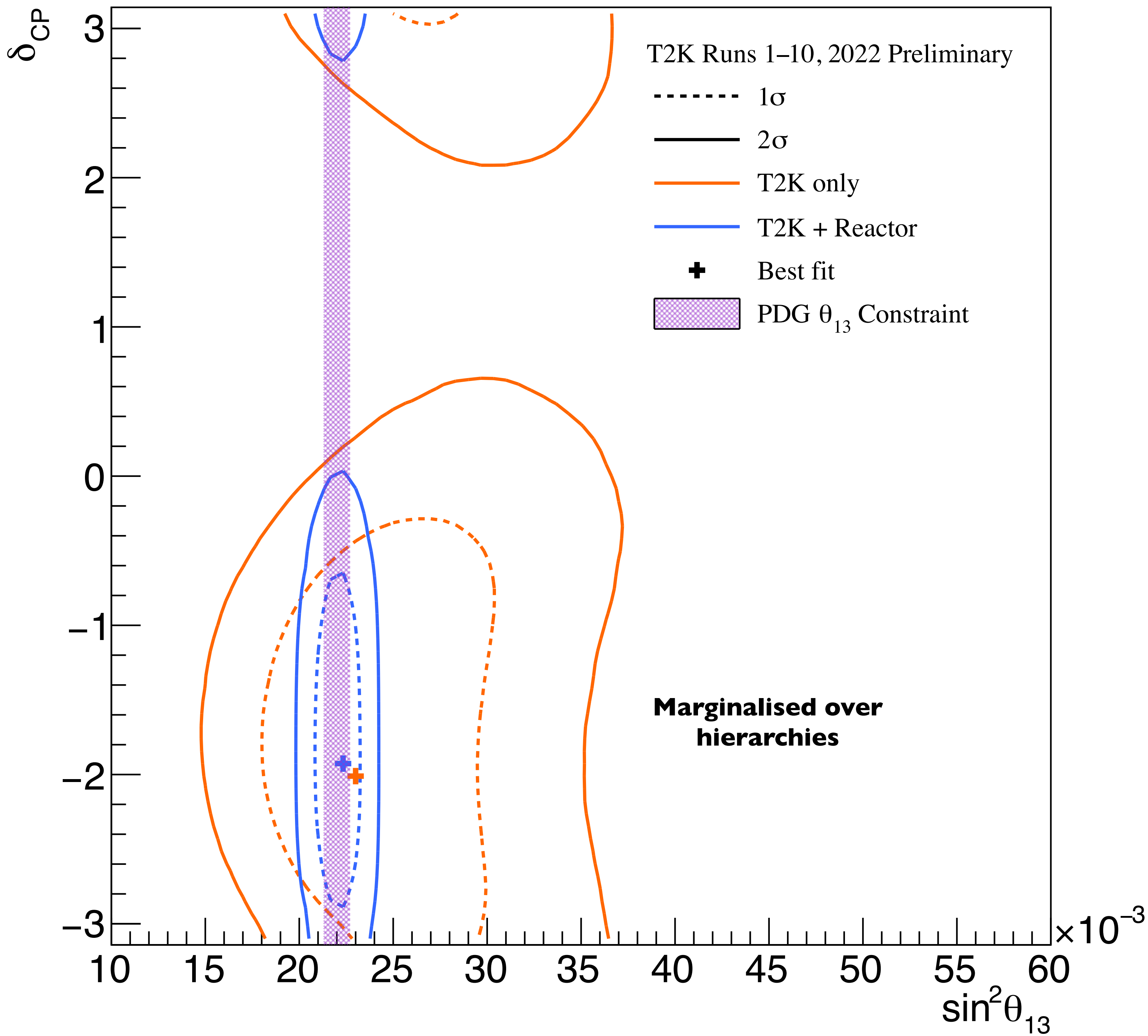
Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6	1.2
Total All	3.4	3.9	4.9	5.2	5.8	14.3	4.5

T2K Run 1-10, preliminary

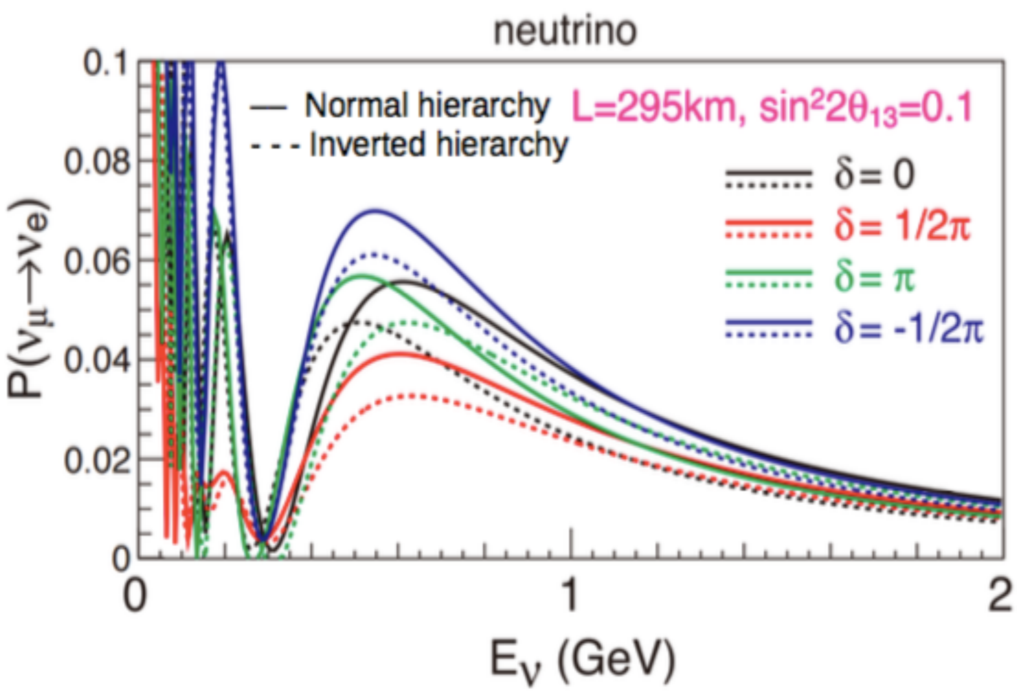
Summary of oscillation results

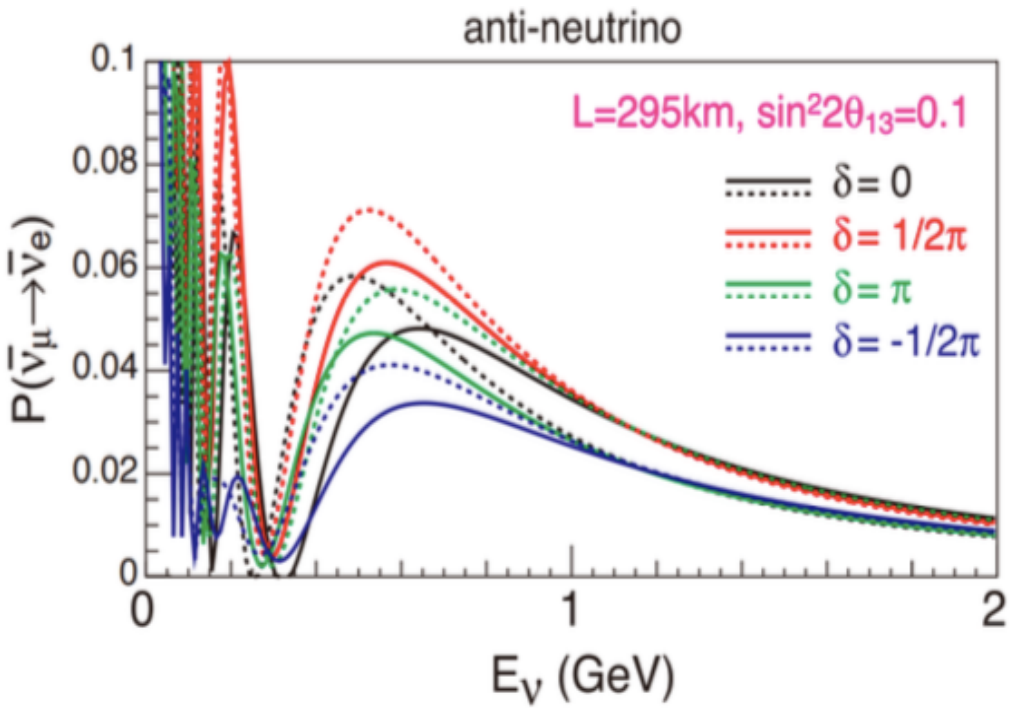


Summary of oscillation results



Summary of oscillation results





T2K upgrades

J-PARC upgrades

- Operation at a higher beam intensity. **750 kW → 1 MW**
- Subsequent upgrade of neutrino beamline to support the beam intensity.
- Horn power supply ramp up for better focusing. **250 kA → 320 kA**
- Expected to be ready for autumn 2023

ND upgrades

- New complex detectors to replace the old P0D detector.
- This will improve our constraints on flux and interaction uncertainties, and also paves way for better xsec measurements.
- Expected to start data taking in 2023

FD upgrades

- Gadolinium was loaded into SK in summer 2020 in different stages with different concentration
- This leads to improved neutron tagging and hence better $\nu/\bar{\nu}$ separation.
- T2K took its Run11 data using SK-Gd, although not yet used in the analysis.