T2K Status and Plans

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on behalf of the T2K collaboration

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Neutrino Oscillations

Oscillations characterised by Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

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

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

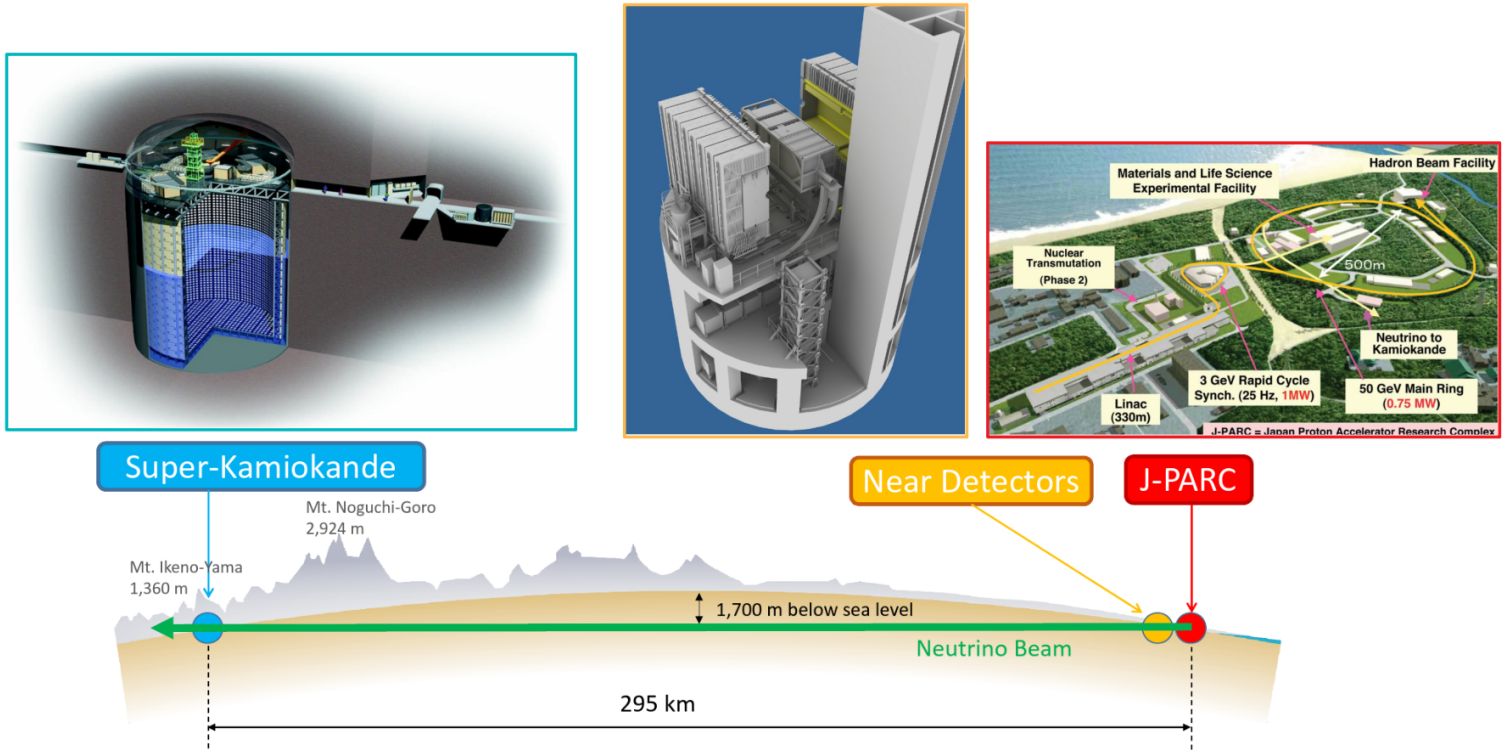
Leads to oscillation probabilities of the form:

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(1.27 \frac{\Delta m^2_{31}[\mathrm{eV}^2] L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

to 0th order, δ_{CP} dependence present at higher orders

Unanswered Questions: what is the value of δ_{CP}?
what is the neutrino mass ordering?
in which octant is θ_{23}?

The T2K Experiment

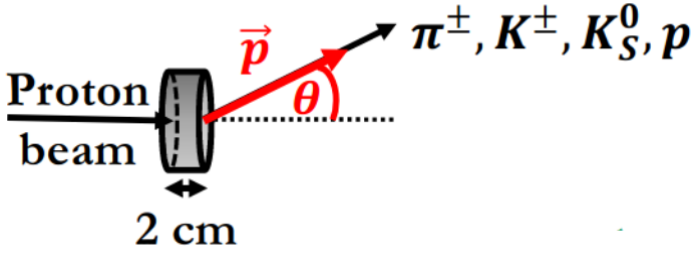


- World-leading measurements of θ_{23}, Δm^2_{32} and δ_{CP}
- Improved measurements of θ_{13} from accelerator neutrinos
- Limited sensitivity to neutrino mass ordering
- Neutrino cross section measurements
- Searches for exotic phenomena

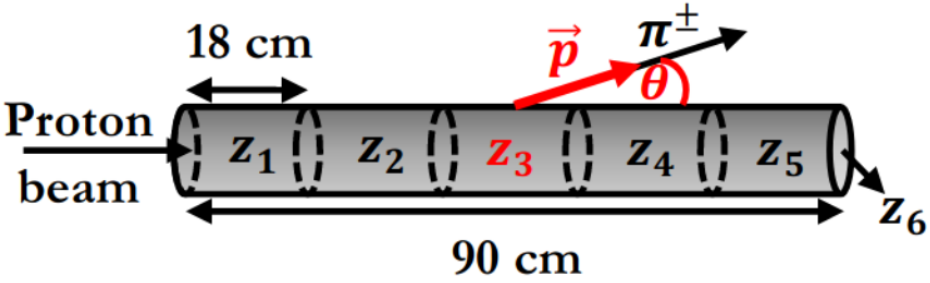
T2K Beam: Flux Model

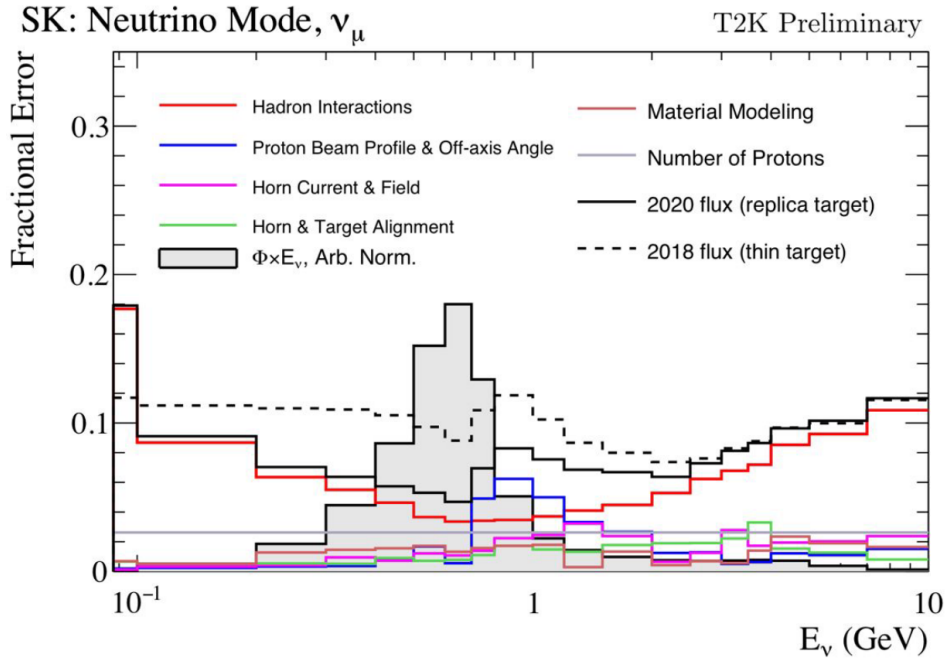
- Use NA61/SHINE hadron production data to inform flux model
- Previously used only thin-target data Eur. Phys. J. C 76, 84 (2016)
- Latest analysis also uses T2K replica-target data Eur. Phys. J. C 76, 617 (2016)
  - → Reduces flux uncertainty from ∼10% to ∼5% in flux peak
  - → Will use even more replica-target data in next oscillation analysis

Thin-target data:



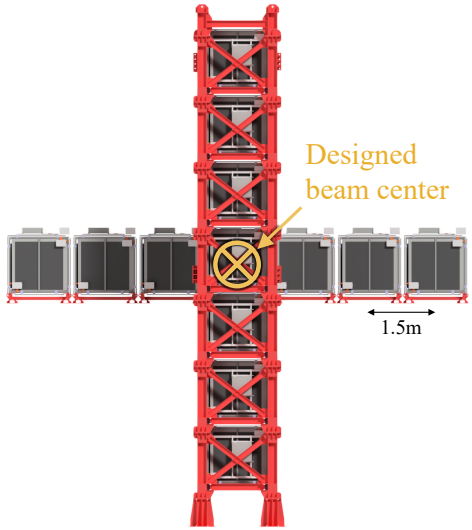
Replica-target data:

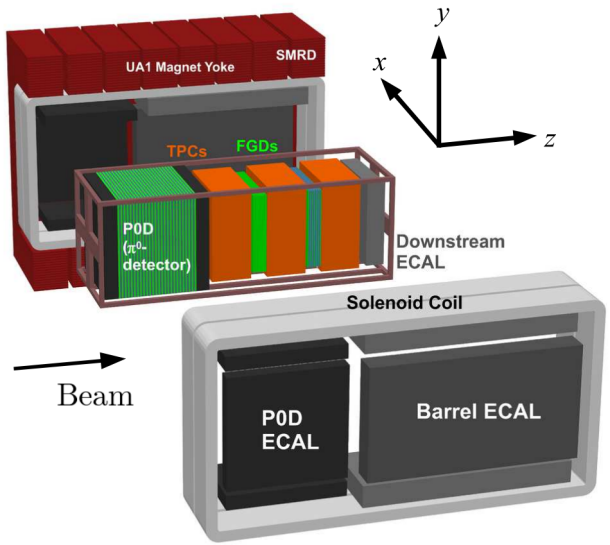




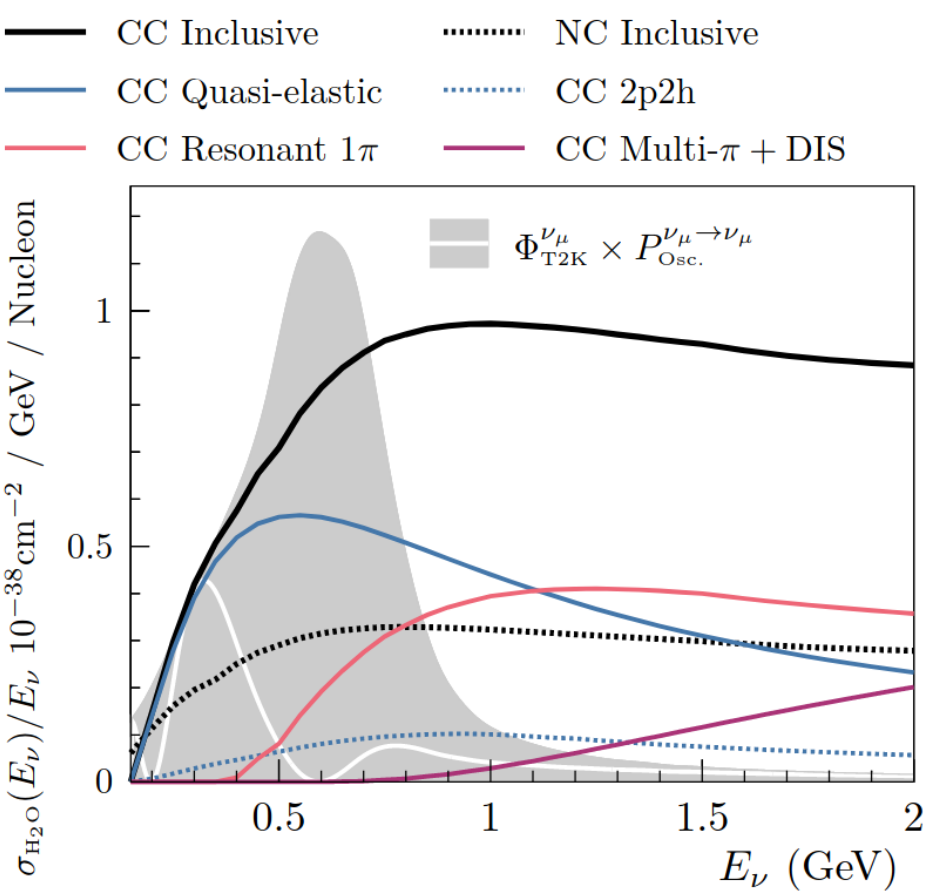
Near Detectors

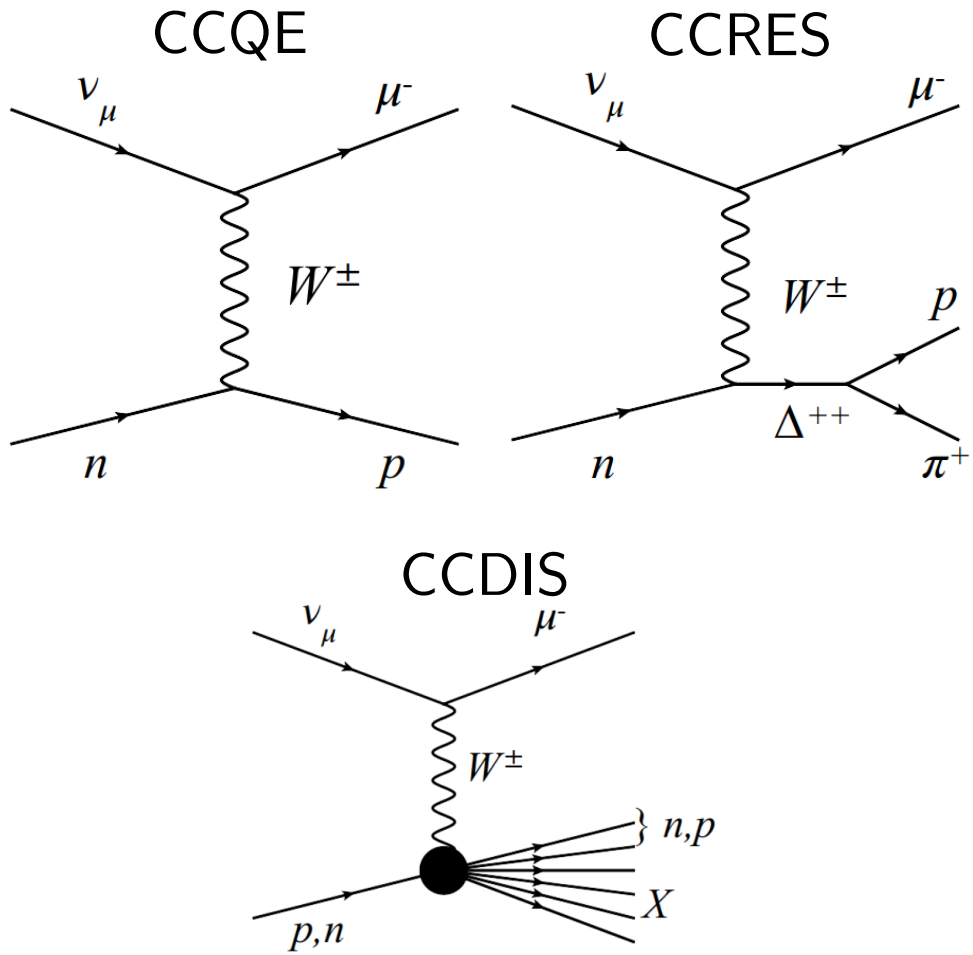
- 280 m downstream of beam target
- INGRID: on-axis detector
  - → Monitor beam intensity, direction & stability
  - → Constrain flux systematics
- ND280: off-axis detector
  - → 2.5° off-axis like Super-K
  - → Consists of several sub-detectors in a 0.2 T magnetic field
  - → Measure neutrino interactions, intrinsic ν_e contribution and wrong-sign background
  - → Constrain flux and cross section uncertainties





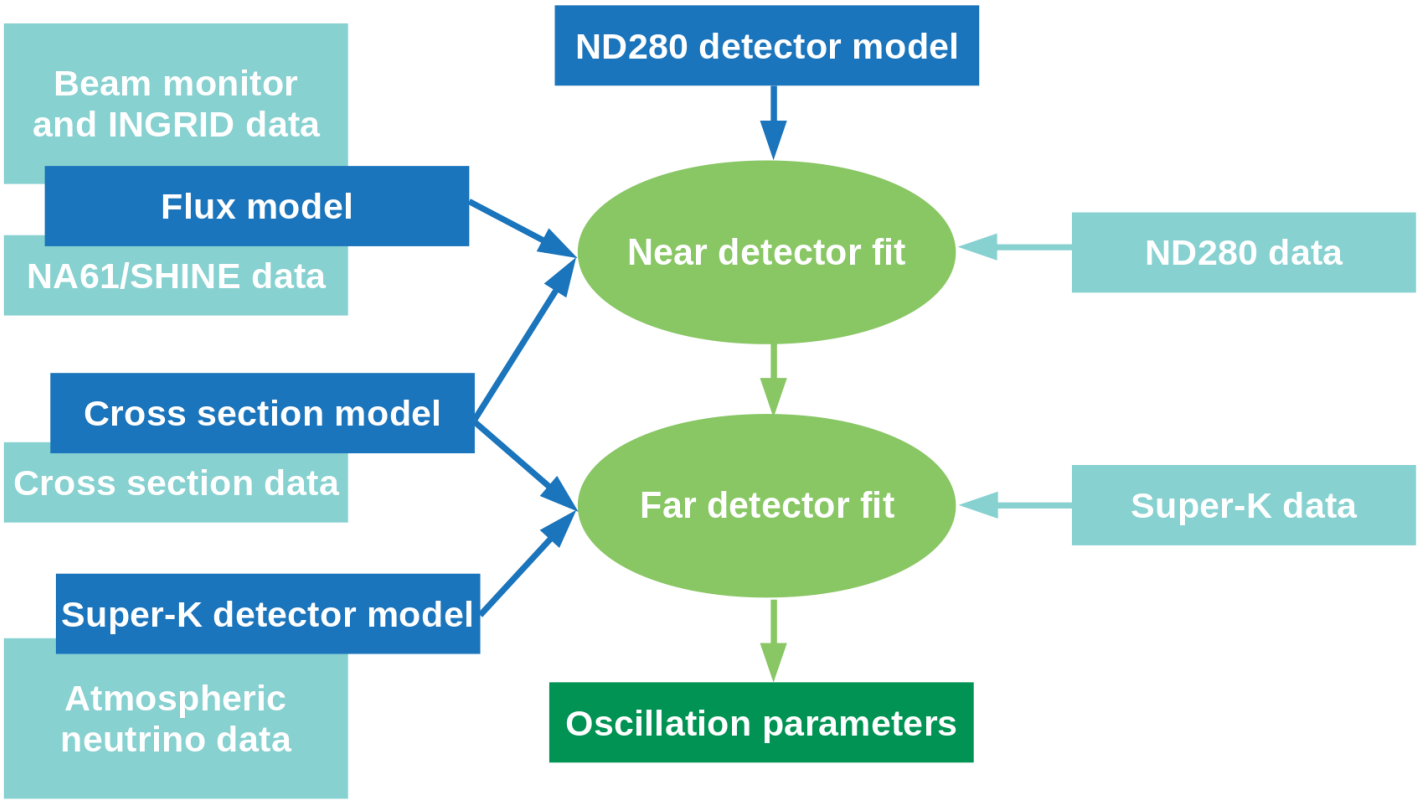
Near Detector Cross Section Measurements





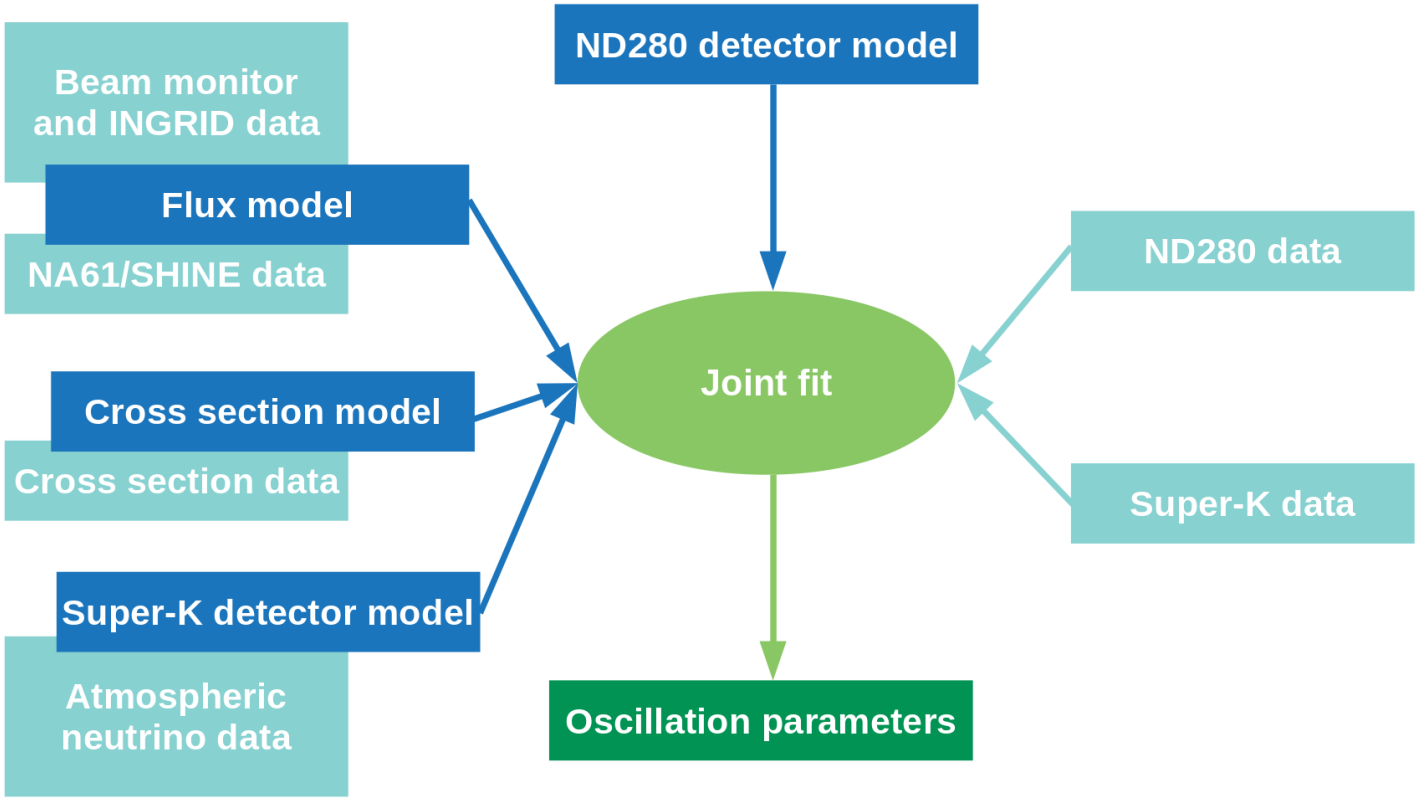
- Cross sections of these processes measured on H_2O and CH
- 7 new cross section results published in last two years

Oscillation Analysis Strategy



- Frequentist oscillation analyses: first fit to near detector data, then fit to Super-K data
- Both fitting approaches produce consistent results

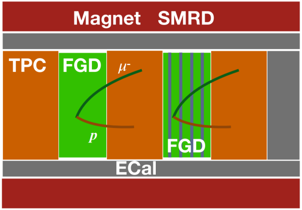
Oscillation Analysis Strategy

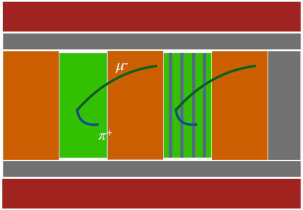


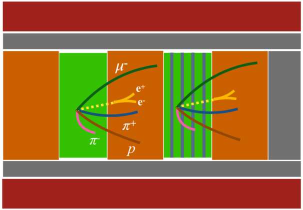
- Bayesian oscillation analysis: simultaneous fit to near and far detector data
- Both fitting approaches produce consistent results

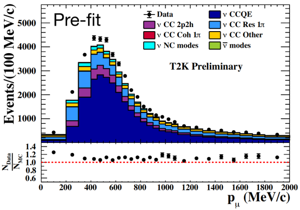
Near Detector Oscillation Samples

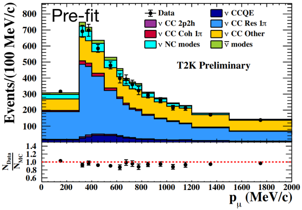
$CC0\pi$	$CC1\pi^+$	CC-Other

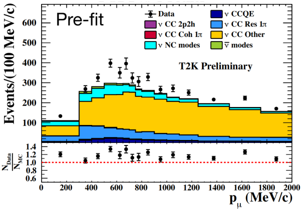








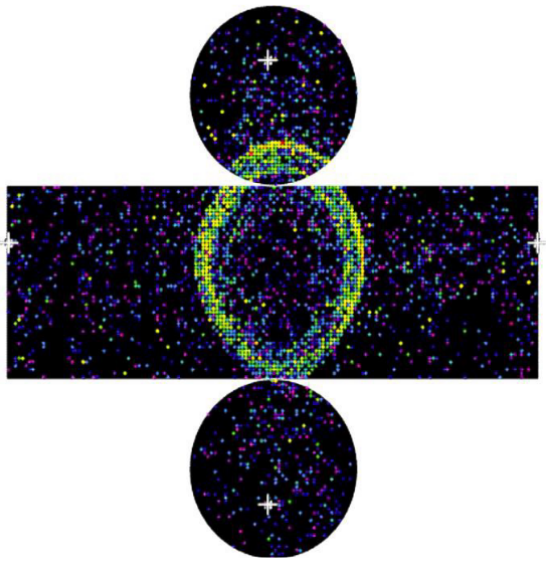




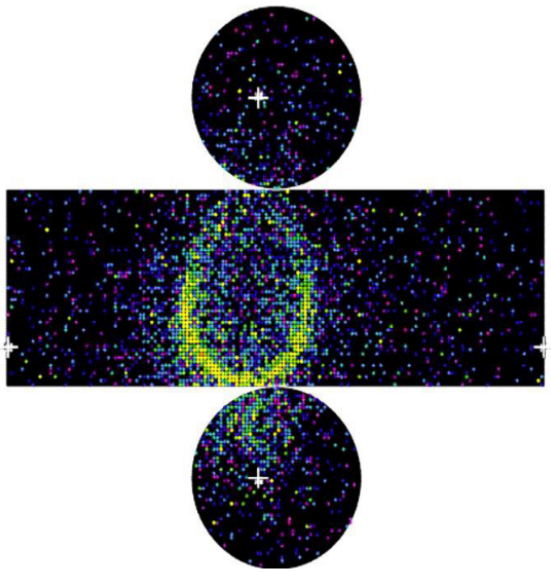
- Have equivalent selections in antineutrino mode, where wrong-sign background (ν_μ) is also selected: <u>improvement to previous analysis</u>
  - → Gives 18 near detector samples in total

Super-Kamiokande

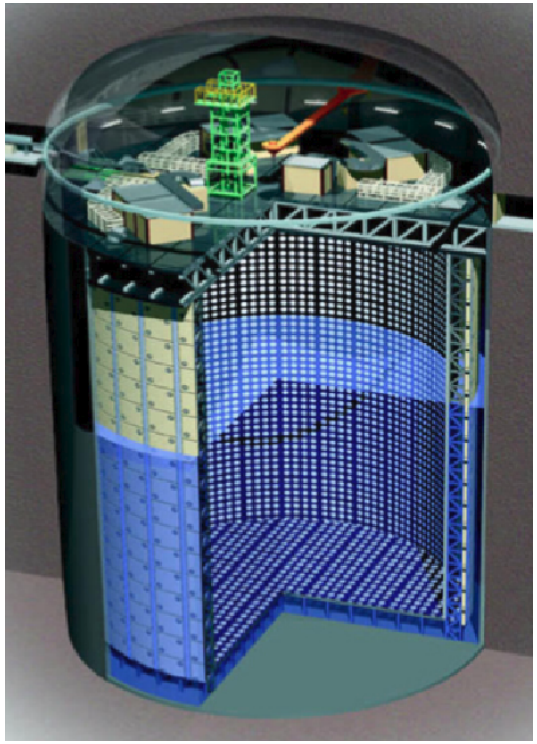
- 2.5° off-axis
- 50 kton water Cherenkov detector
- Being loaded with $Gd_2(SO_4)_3$ to improve neutron tagging efficiency
  - → ∼90% capture, ∼90% reconstruction



muon



electron



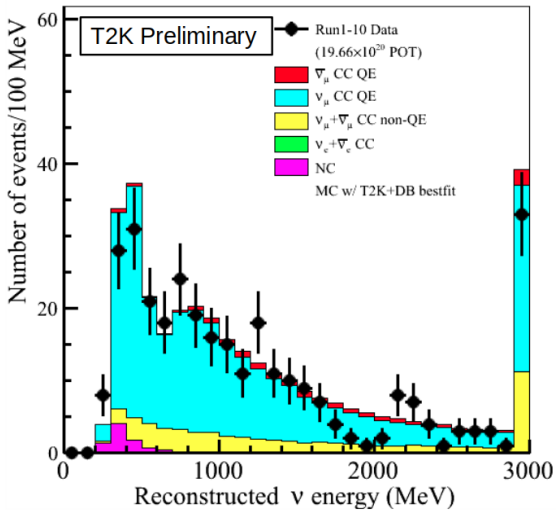
- Excellent particle identification capability
- $< 1\%$ μ mistaken as e
- μ produce sharp rings
- e produce fuzzy rings

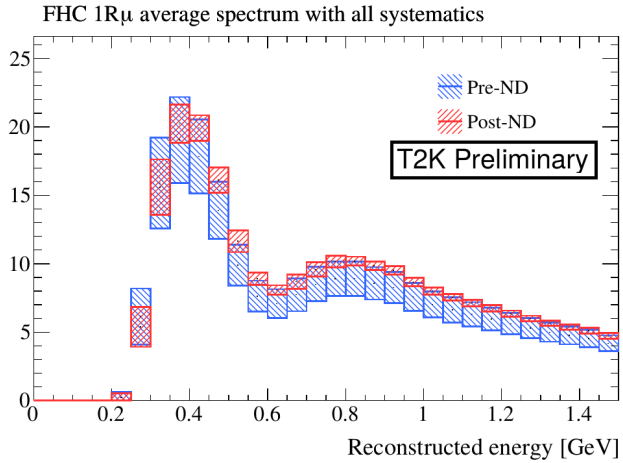
Far Detector Oscillation Samples

5 far detector samples:

- 1 μ-like ring, 1Rμ, in ν and $\bar{\nu}$ modes
- 1 e-like ring, 1Re, in ν and $\bar{\nu}$ modes
- 1 e-like ring + Michel electron ring, 1Re1de, in ν-mode

ν-mode 1Rμ

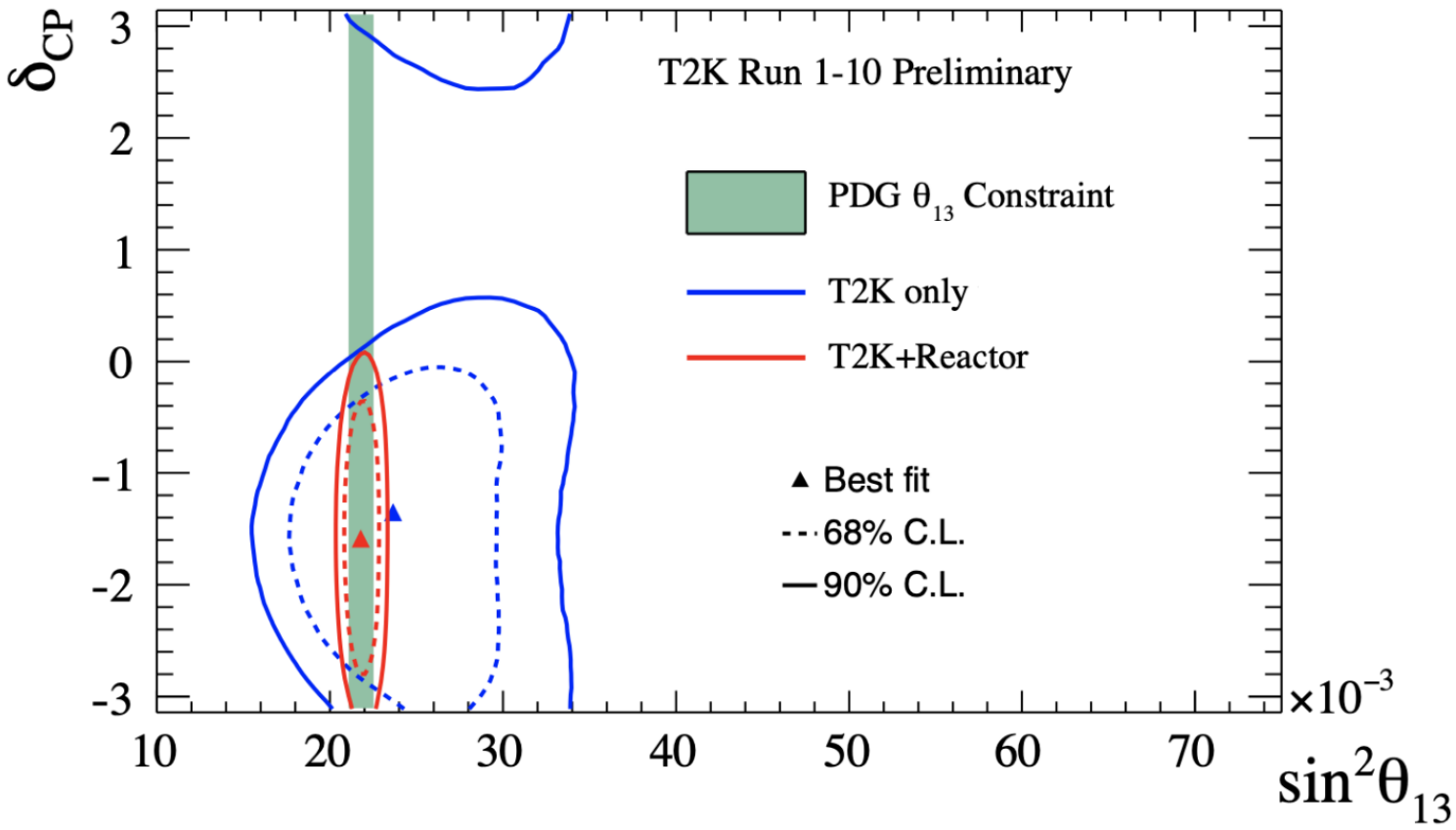




Systematic uncertainties are constrained by near detector (ND) fit:

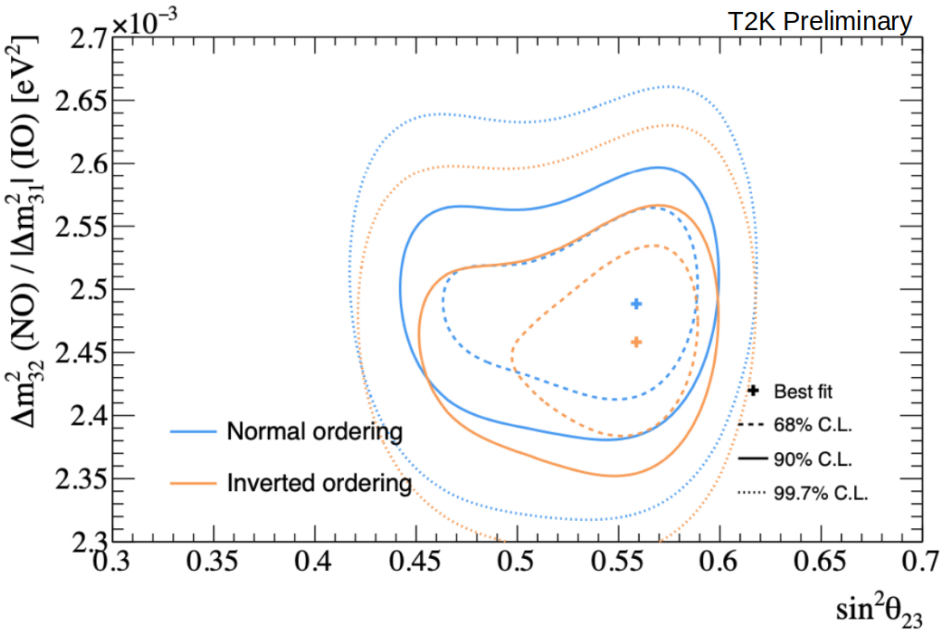
Systematic Uncertainty	1Rμ		1Re		
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π^+
Pre-ND	11.1%	11.3%	13.0%	12.1%	18.7%
Post-ND	3.0%	4.0%	4.7%	5.9%	14.3%

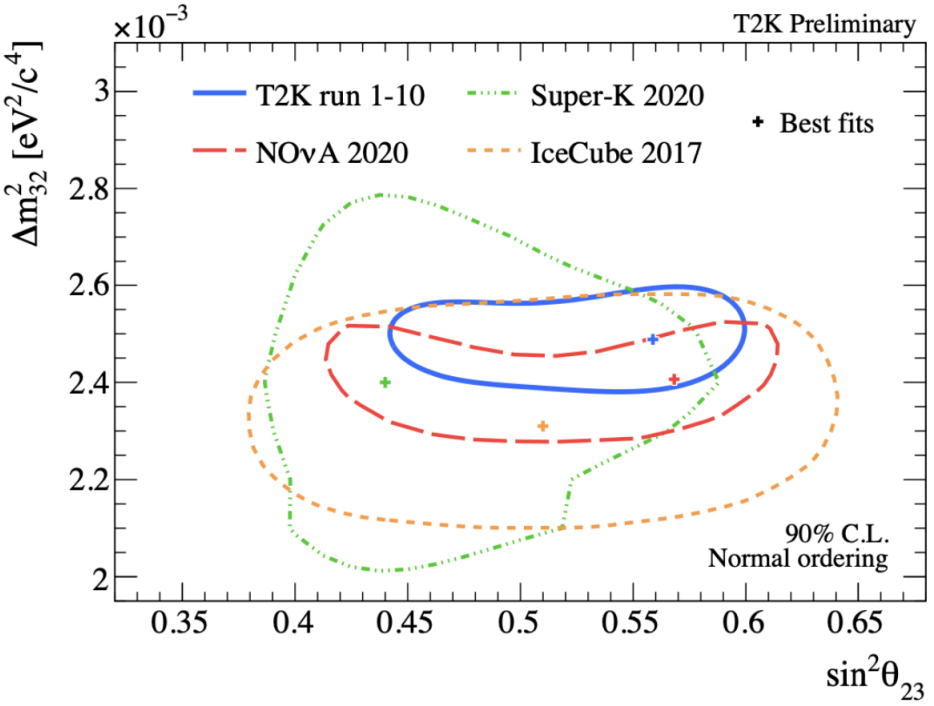
Measuring θ_{13}



- Measure θ_{13} with and without external reactor constraint (PDG 2019)
- Good agreement between T2K result and reactor data
- When studying other PMNS parameters, reactor constraint is included

Measuring θ_{23} and Δm^2_{32}

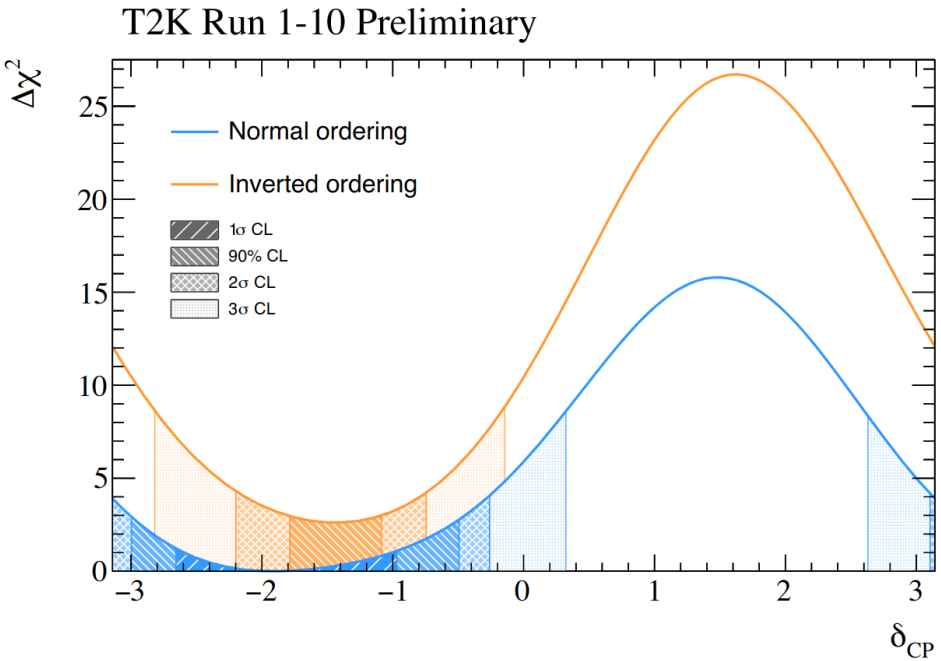


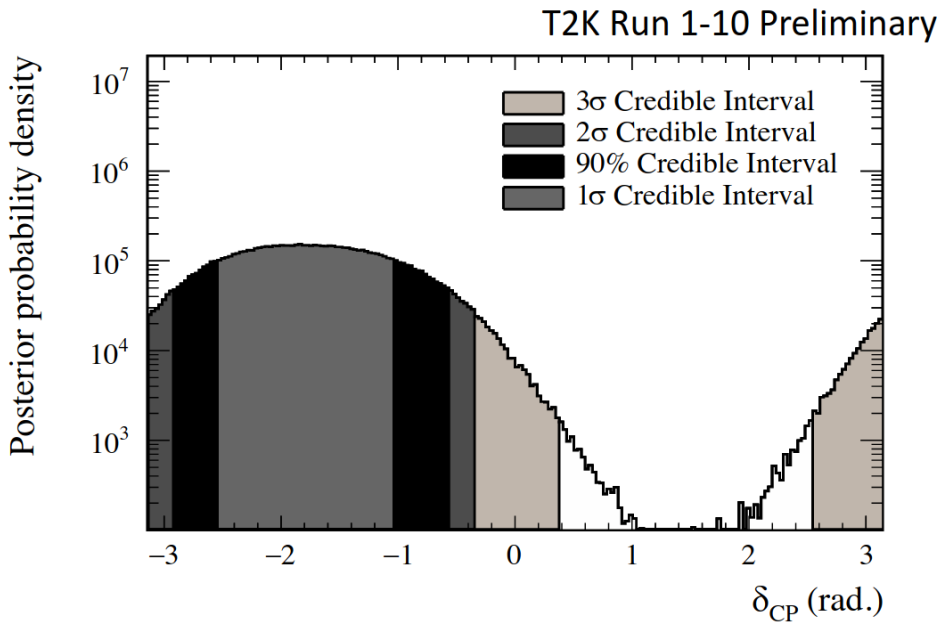


- Slight preference for upper octant and normal ordering

Posterior Probability	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IO ($\Delta m^2_{32} < 0$)	0.035	0.157	0.192
Sum	0.230	0.770	1.000

CP-Violation

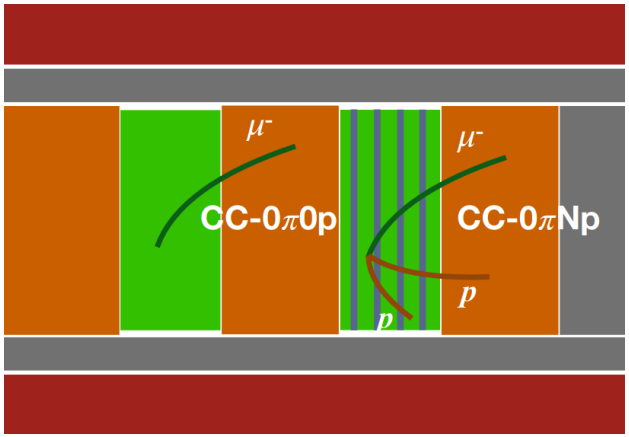




- 35% of values excluded at 3σ, marginalised across mass orderings
- CP-conserving values $(0,\pi)$ excluded at 90%, π not quite at 2σ
- Have demonstrated robustness of fit against wide range of biases
  - $\rightarrow$ Largest $\Delta\chi^2$ changes seen would cause left (right) edge of 90% interval to move by 0.073 (0.080), and conclusions would remain the same

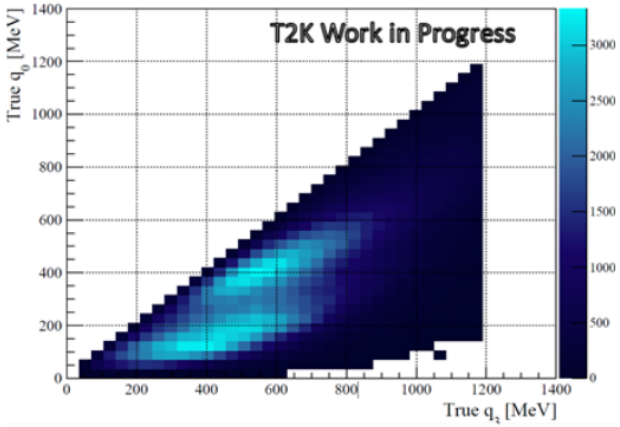
Going Beyond the 2020 Result

New Samples in Oscillation Analysis: Near Detector

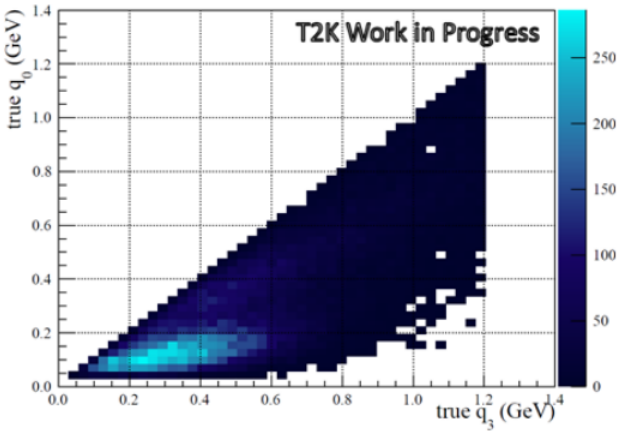


- Split CC0π sample based on presence or absence of **protons**
- Different sensitivity to nuclear effects:
  - $\rightarrow$ Nieves et al. model describing 2p2h interactions has two peak structure

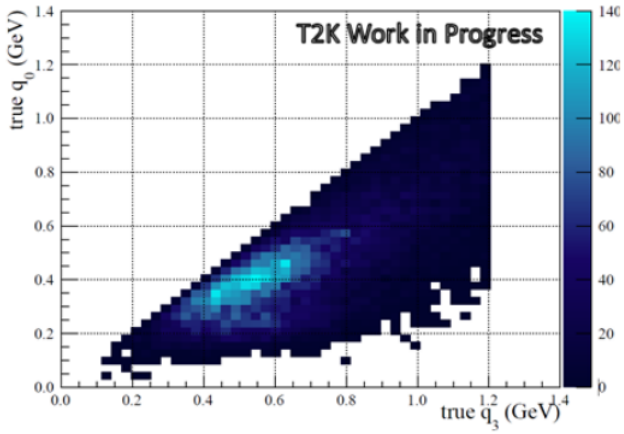
Nieves et al.



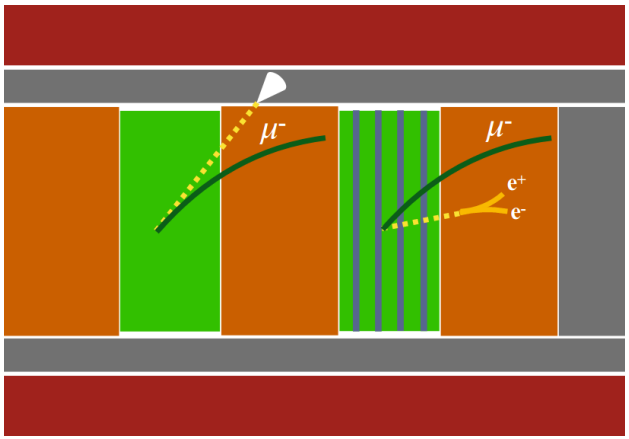
CC0π0p



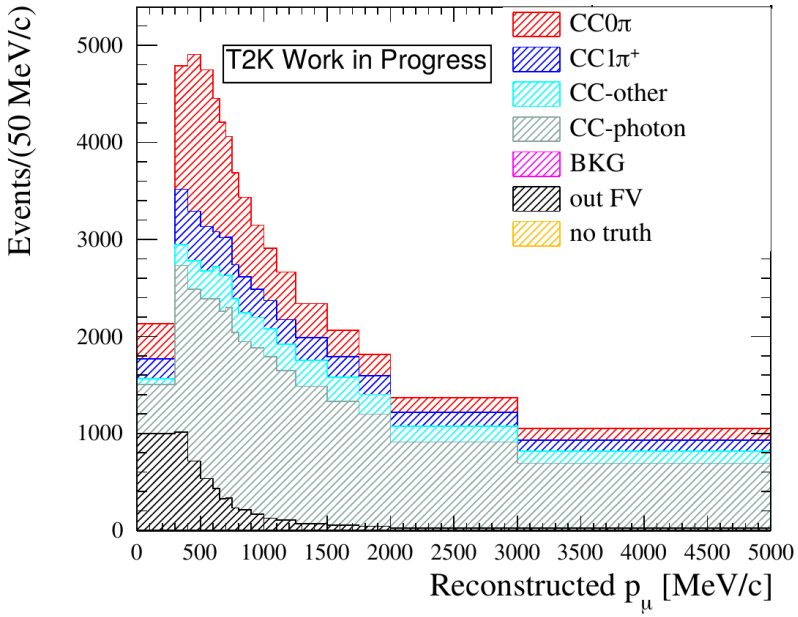
CC0πNp

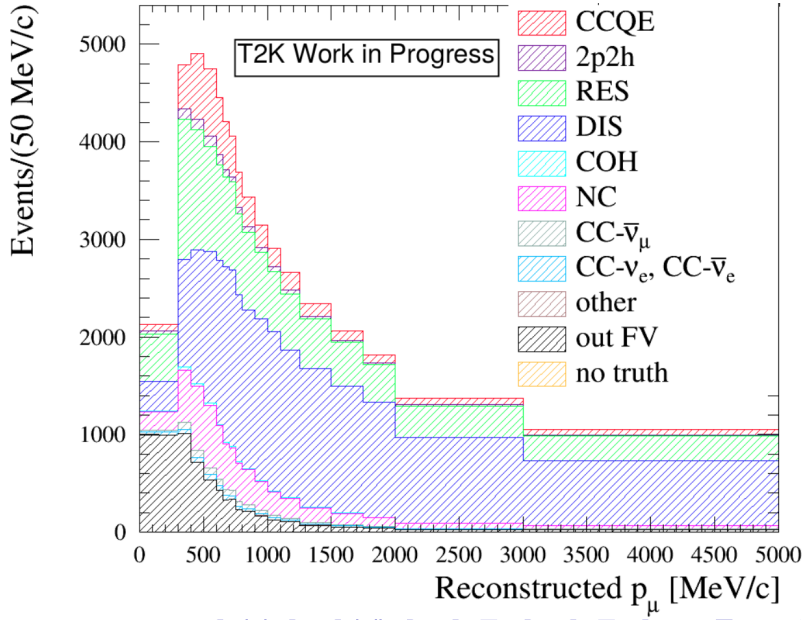


New Samples in Oscillation Analysis: Near Detector



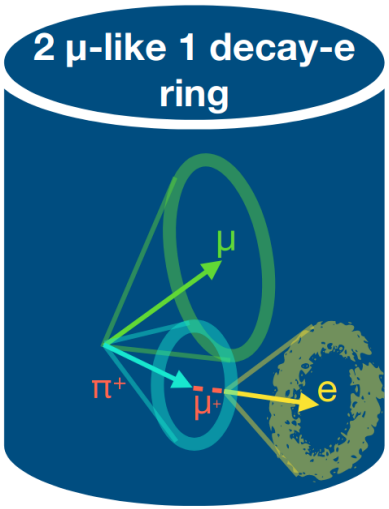
- Isolate CCπ^0 interactions by looking for **photons** in the ECals and TPCs
- Dominated by DIS (30%) and multi-pion production (20%), with contribution from resonant π^0 production (24%)
- Improves purities of other ND samples

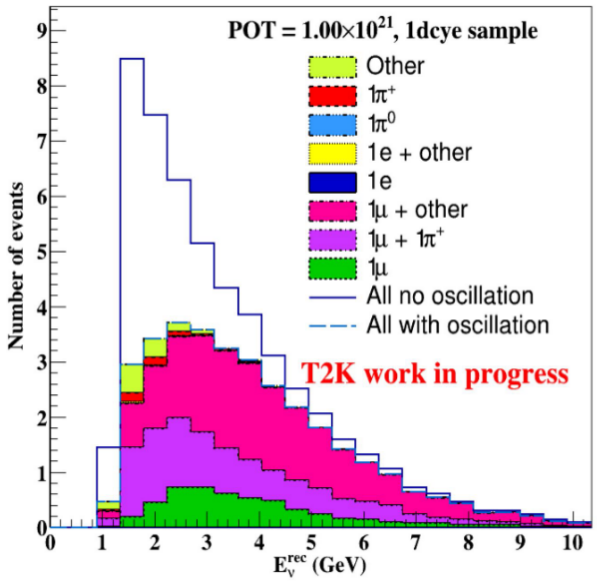


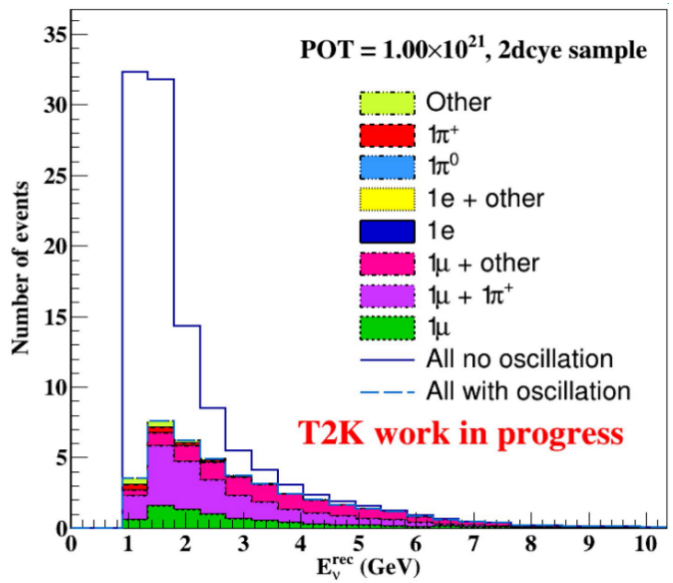


New Samples in Oscillation Analysis: Far Detector

- ν_μ CC events with 2 μ-like rings and 1 or 2 decay-e
- $\sim$20% more events selected at SK
- Expected to give slight increase in sensitivity to θ_{23} and $|\Delta m^2_{32}|$
- Complementary sample to other SK pion sample

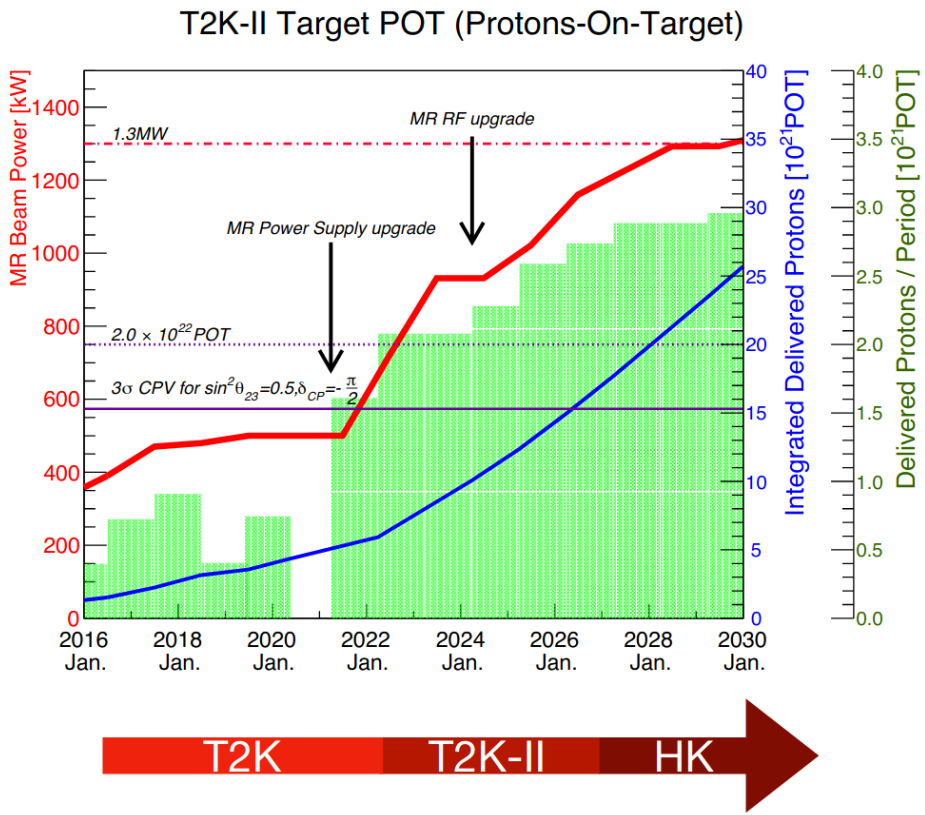






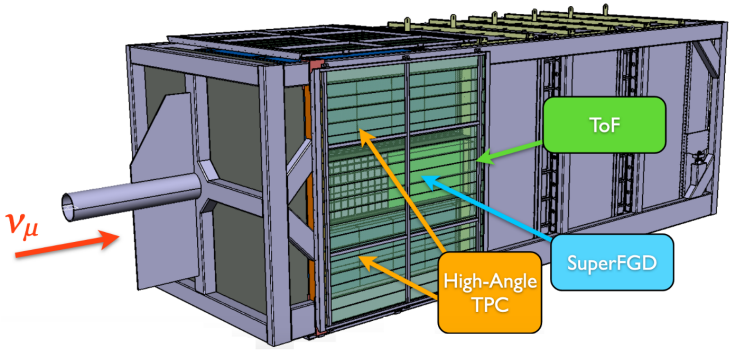
Beam Upgrade

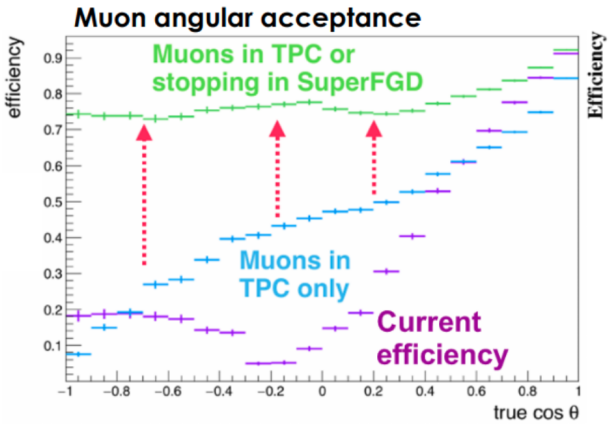
- Beam stable at 515 kW during last run
- Main ring power supply upgrade
  - → Expect beam power > 800 kW
- RF upgrade and machine development
  - → Expect beam power > 1 MW by 2027

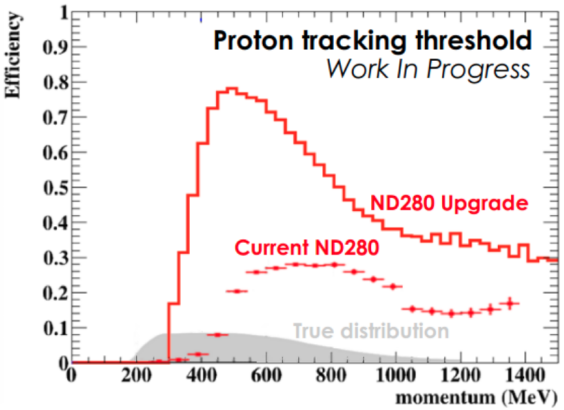


ND280 Upgrade: Coming 2022

- Replace PØD with:
  - → SuperFGD: 2 million 1 cm cubes of scintillator with individual readout
  - → High Angle TPCs equipped with resistive MicroMegas
  - → Time-of-Flight detectors



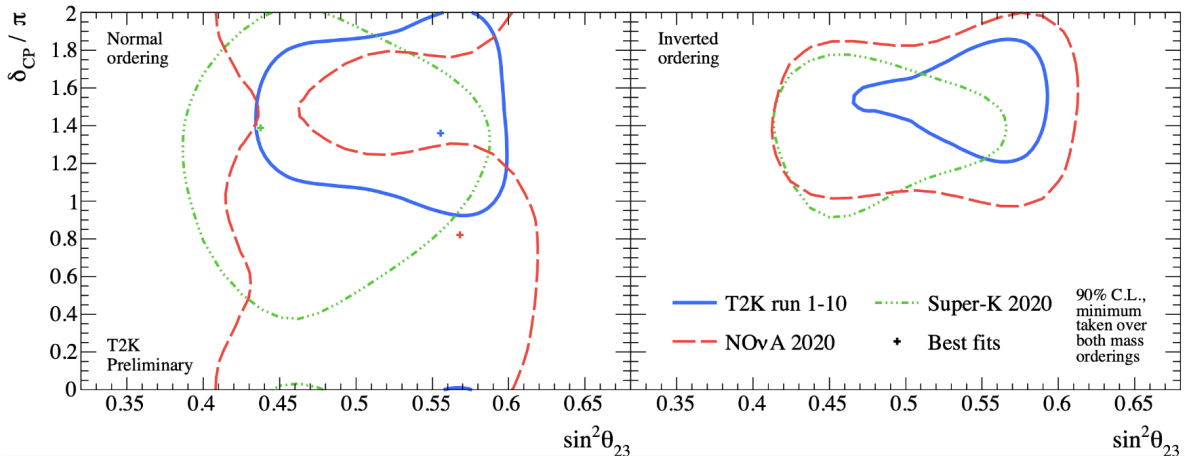




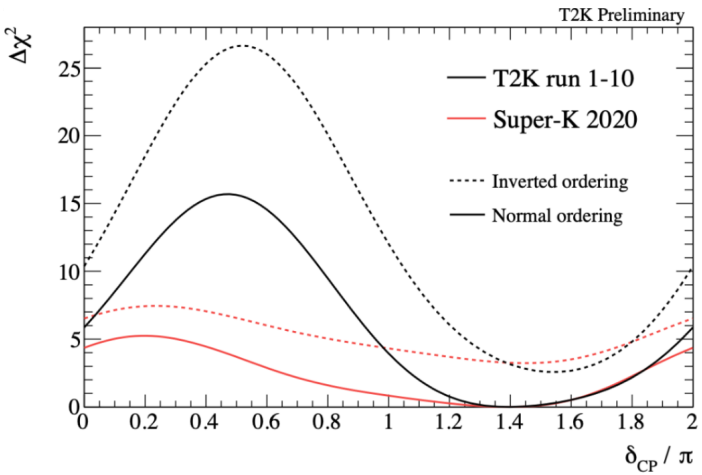
- Improved efficiency
- Lower proton threshold
- Neutron kinematics
- Increased target mass
- Reduction of key systematic uncertainties

Joint Fits

T2K-NOνA



T2K-SK

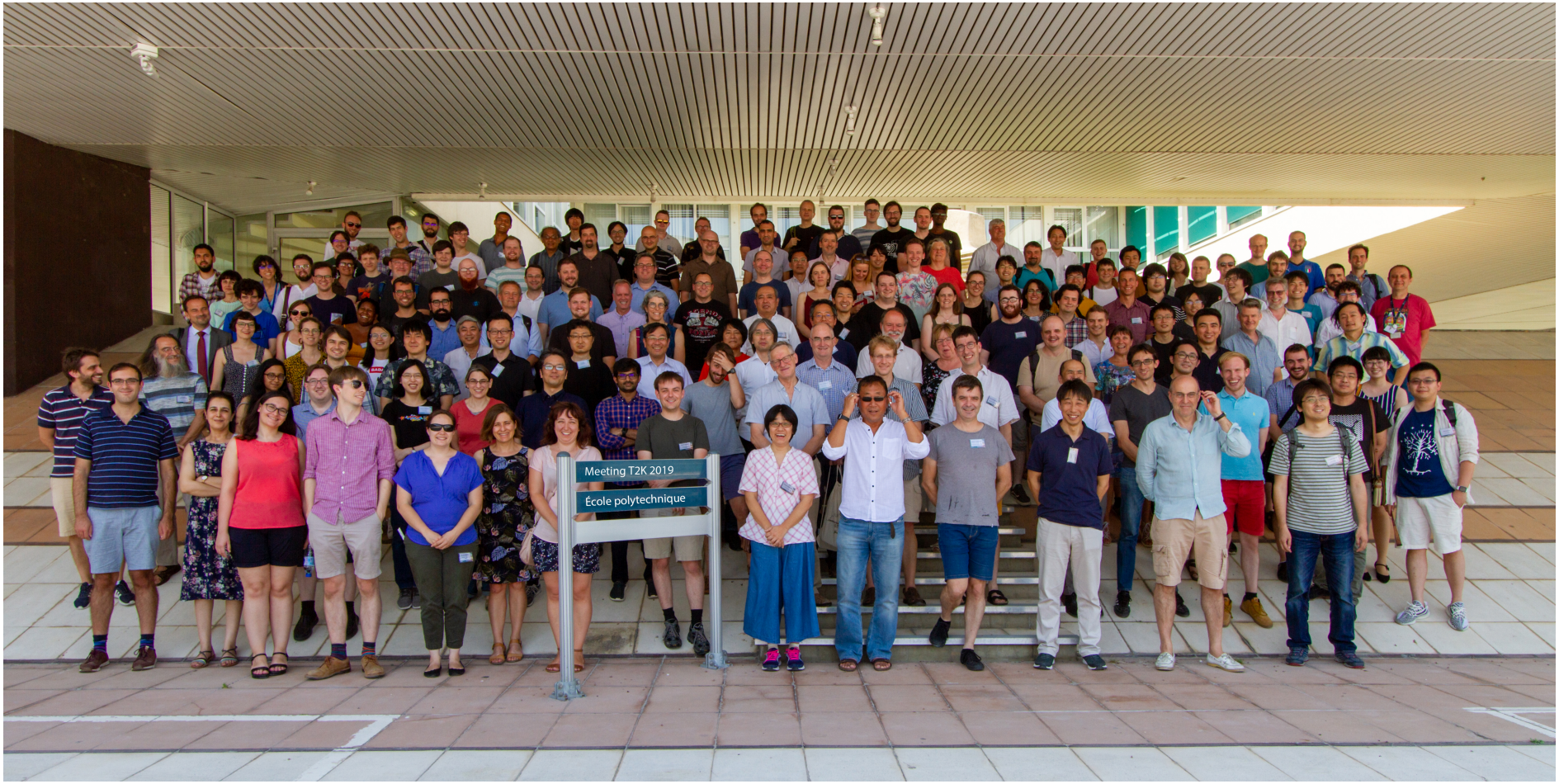


- Two joint fits with other experiments currently ongoing
- Combining data from experiments of different energies and baselines
- Joint fits are crucial to breaking degeneracies and understanding systematic correlations between experiments
- Allows consistent statistical treatment using full experiment likelihoods with all oscillation parameters correlated

Summary

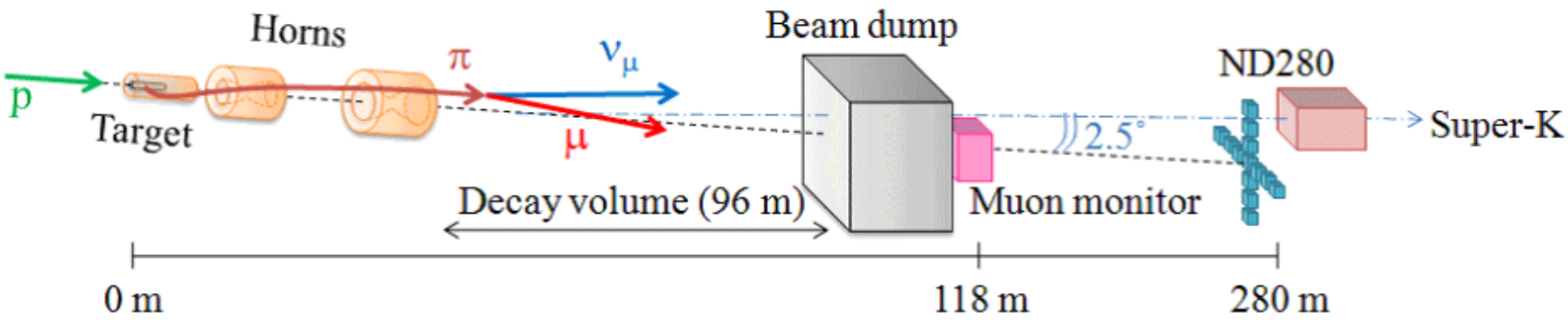
- T2K is producing world-leading measurements of PMNS parameters
- 7 cross section results published in the last two years
- Latest oscillation results show:
  - → CP-conservation is excluded at 90%
  - → There is slight preference for normal ordering and upper octant
- New near and far detector samples coming in next oscillation analysis
  - → And even more samples coming in future iterations!
- Beam and ND280 upgrades in coming years
- Many more developments I didn't have time to discuss:
  - → Increased statistics - latest data taken with SK-Gd (0.01%)
  - → New off-axis detectors: WAGASCI and Baby-MIND
  - → New cross section model and measurements

Thank You!

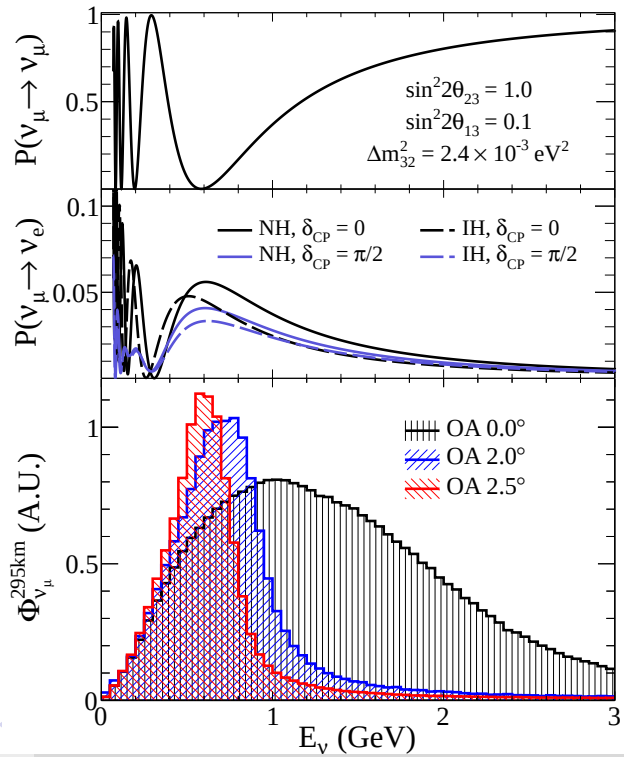


BACKUP

The T2K Beam

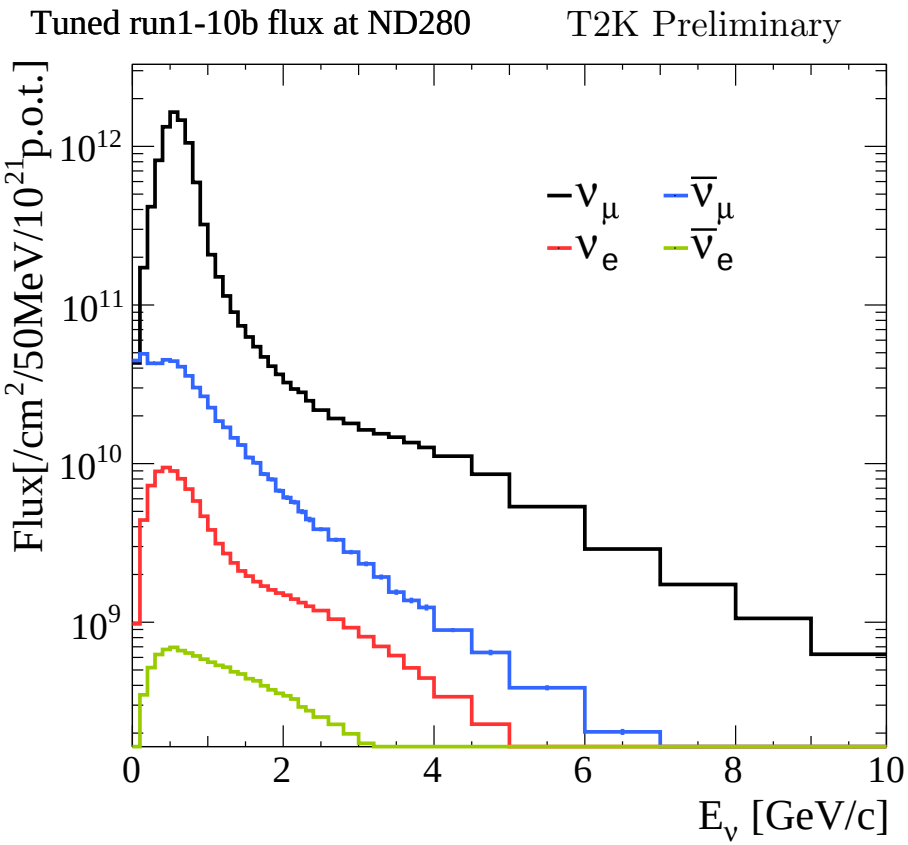


- 30 GeV proton beam extracted from J-PARC main ring onto graphite target
  - → Produces hadrons: mostly pions and kaons
- Hadrons are charge-selected and focused by three magnetic horns
  - → Select positive hadrons to produce predominantly ν_μ beam
  - → Select negative hadrons to produce predominantly $\bar{\nu}_\mu$ beam
- Beam directed 2.5° away from Super-K

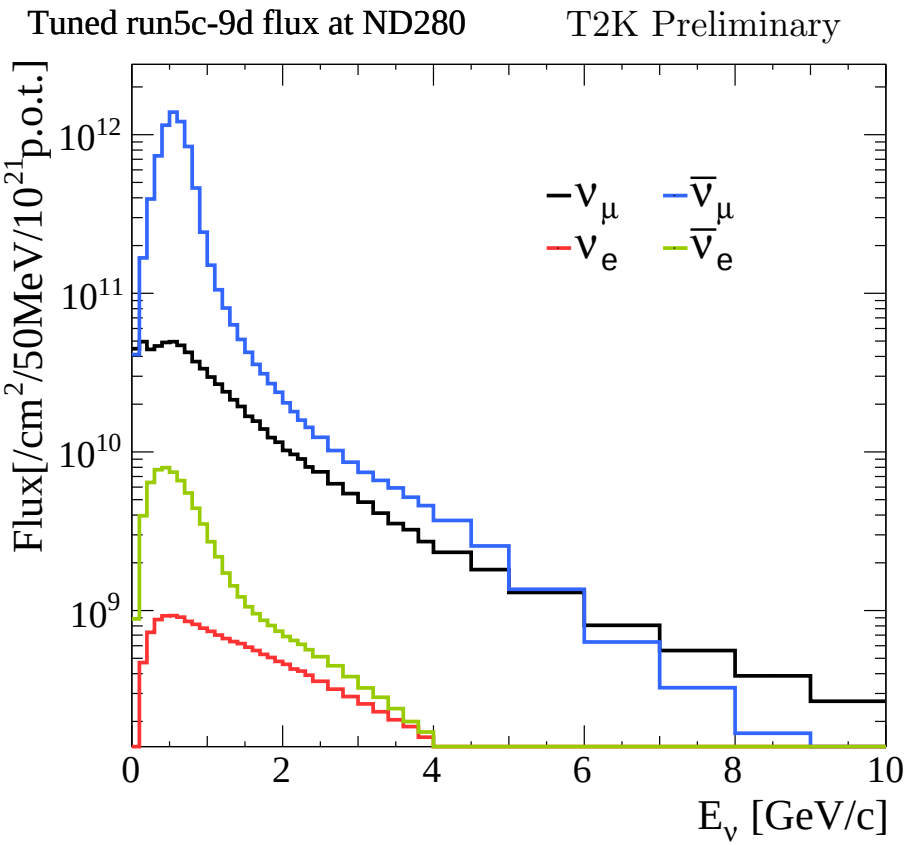


Beam Composition

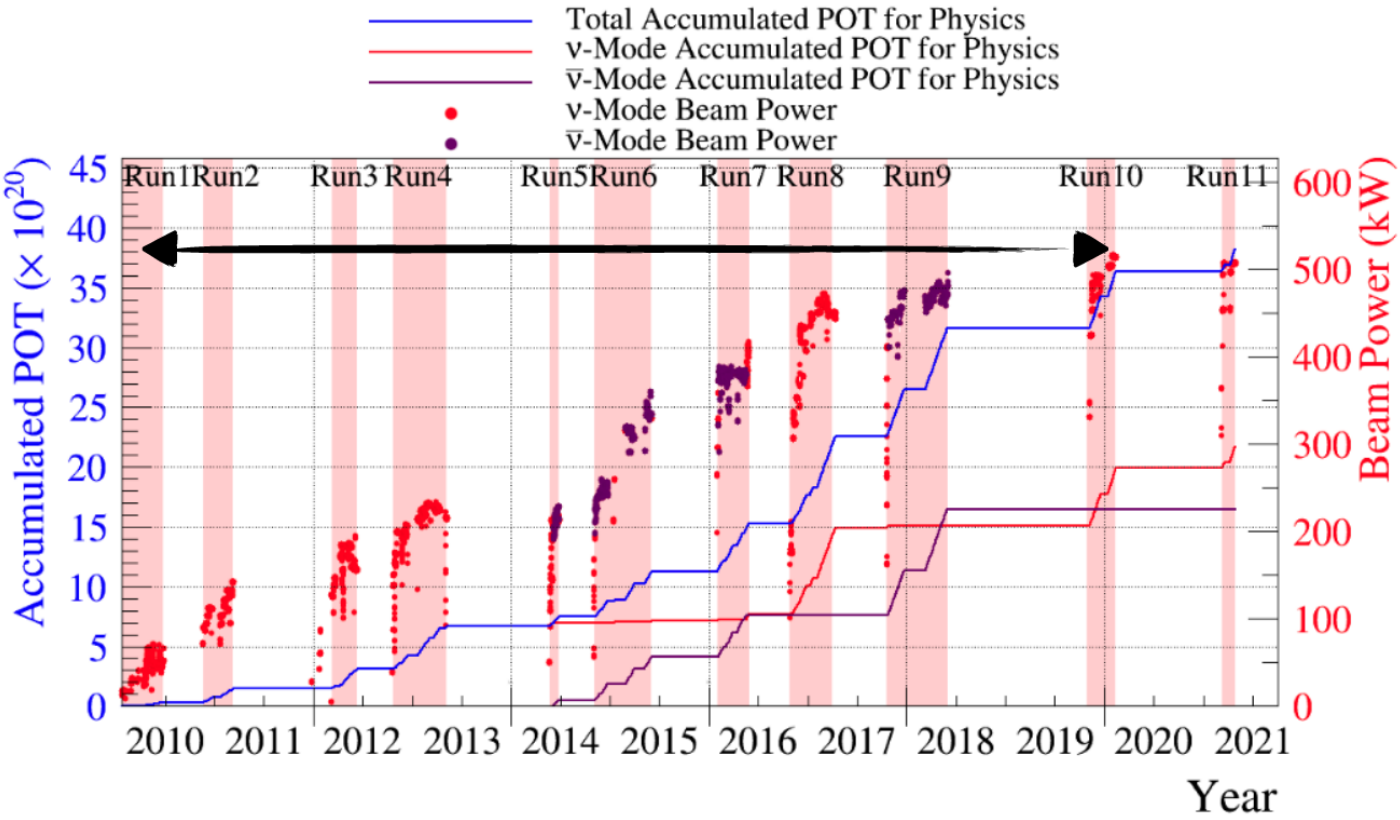
ν-mode



$\bar{\nu}$-mode



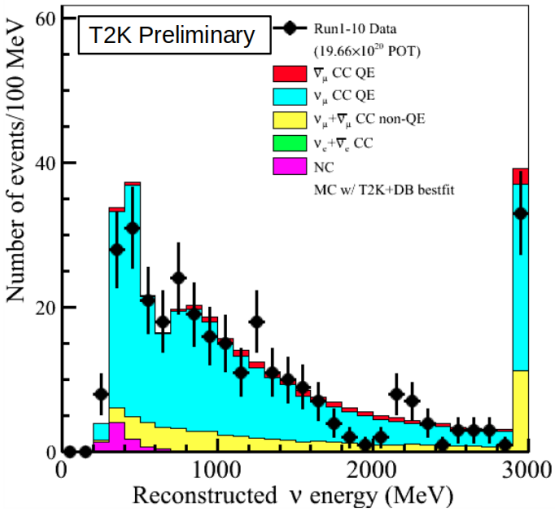
T2K Data Collection



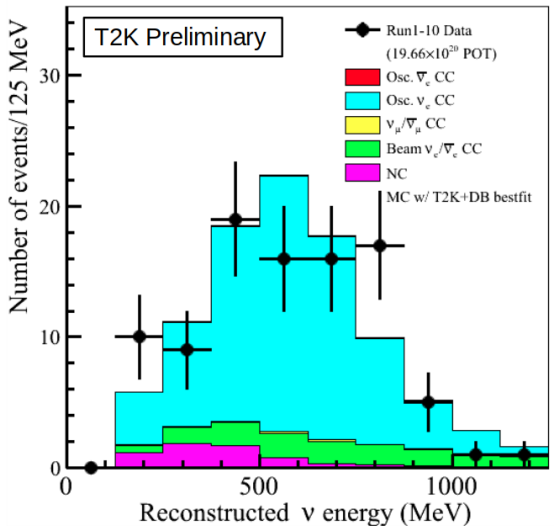
- Total POT $= 3.8 \times 10^{21}$
- ν-mode 2.2×10^{21} (56.8%); $\bar{\nu}$-mode 1.6×10^{21} (43.2%)
- Oscillation results presented use 3.6×10^{21} POT

Far Detector Oscillation Samples

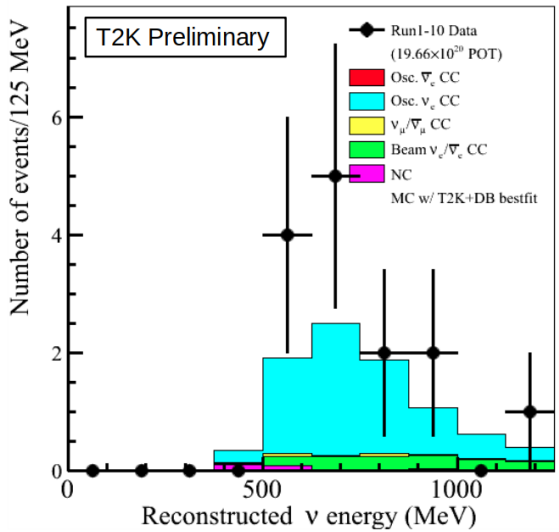
ν-mode 1Rμ



ν-mode 1Re



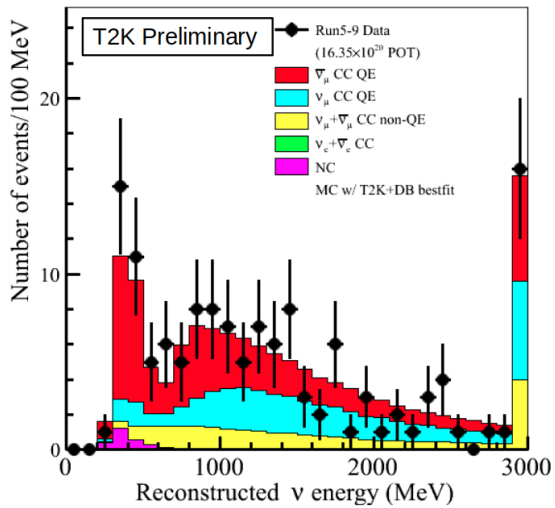
ν-mode 1Re1de



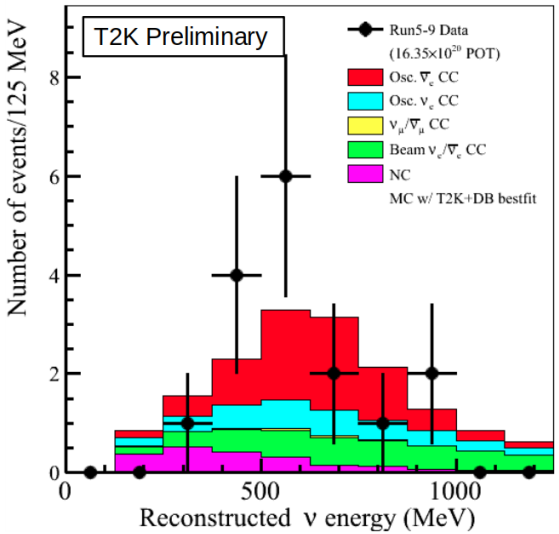
5 far detector samples:

- 1 μ-like ring, 1Rμ, in ν and $\bar{\nu}$ modes
- 1 e-like ring, 1Re, in ν and $\bar{\nu}$ modes
- 1 e-like ring + Michel electron ring, 1Re1de, in ν-mode

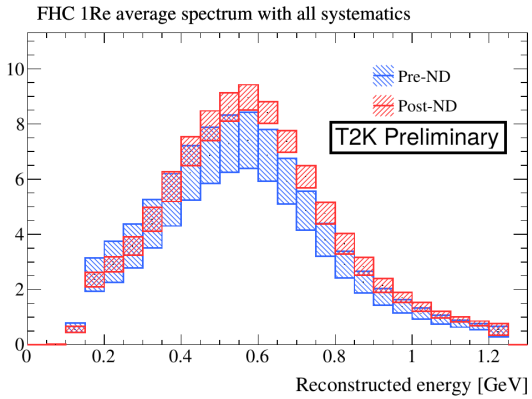
$\bar{\nu}$-mode 1Rμ

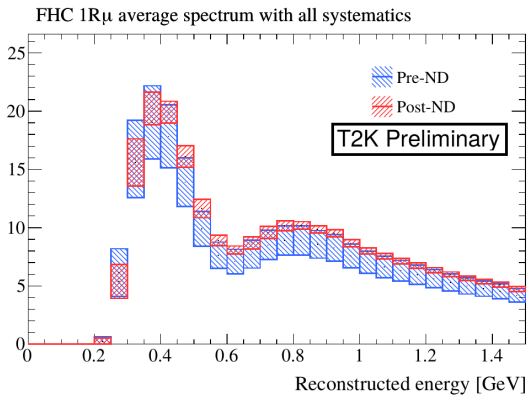


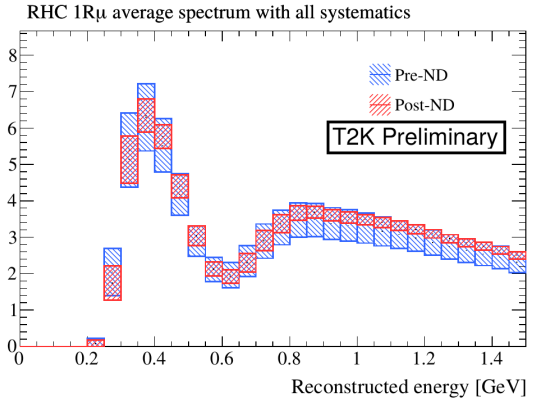
$\bar{\nu}$-mode 1Re

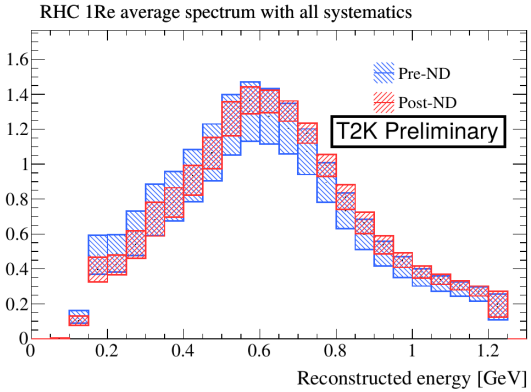


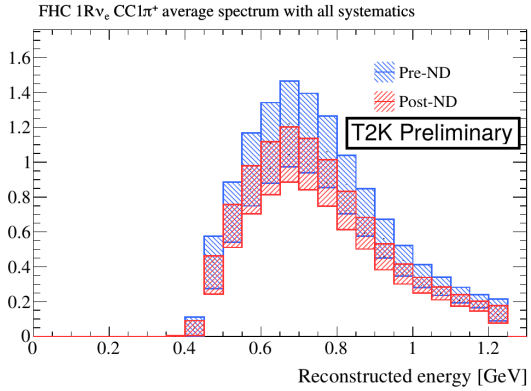
Impact of Near Detector Fit











Systematic Uncertainty	1Rμ ν-mode	1Rμ $\bar{\nu}$-mode
Pre-ND	11.1%	11.3%
Post-ND	3.0%	4.0%

Systematic Uncertainty	1Re ν-mode	1Re $\bar{\nu}$-mode	1Re ν-mode CC1π^+
Pre-ND	13.0%	12.1%	18.7%
Post-ND	4.7%	5.9%	14.3%

Impact of Near Detector Fit

Pre-fit Systematic Uncertainties

Systematic Source	1Rμ		1Re		
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π^+
Flux	5.1%	4.7%	4.8%	4.7%	4.9%
Cross section (all)	10.1%	10.1%	11.9%	10.3%	12.0%
SK+SI+PN	2.9%	2.5%	3.3%	4.4%	13.4%
Total	11.1%	11.3%	13.0%	12.1%	18.7%

Post-fit Systematic Uncertainties

Systematic Source	1Rμ		1Re		
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π^+
Flux	2.9%	2.8%	2.8%	2.9%	2.8%
Xsec (ND constr)	3.1%	3.0%	3.2%	3.1%	4.2%
Flux+Xsec (ND constr)	2.1%	2.3%	2.0%	2.3%	4.1%
Xsec (ND unconstrained)	0.6%	2.5%	3.0%	3.6%	2.8%
SK+SI+PN	2.1%	1.9%	3.1%	3.9%	13.4%
Total	3.0%	4.0%	4.7%	5.9%	14.3%