The XXX International Conference on Neutrino Physics and Astrophysics – Neutrino 2022

Recent results and future prospects from T2K

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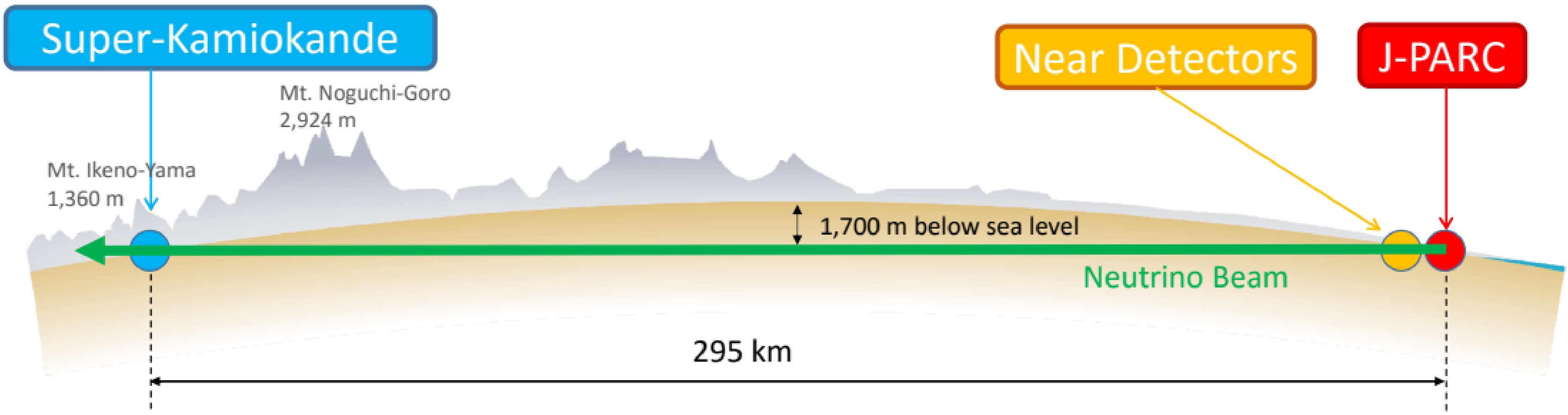
June 1st, 2022

Outline

- The T2K experiment
  - ➔Overview
  - ➔Physics goals
  - ➔Sensitivity to neutrino oscillation
- New results on neutrino oscillation
  - ➔Analysis update
  - ➔New result
- Highlight of cross-section measurements
- Future perspective
  - ➔Joint analyses
  - ➔Neutron tagging using Gd
  - ➔Upgrade of accelerator and near detectors

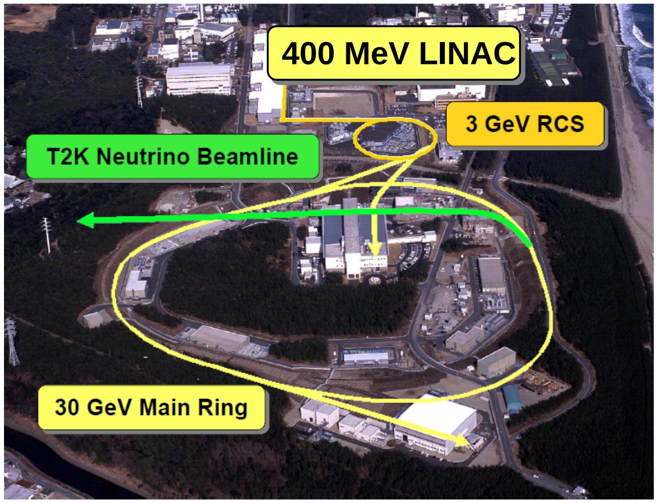
The T2K experiment Overview

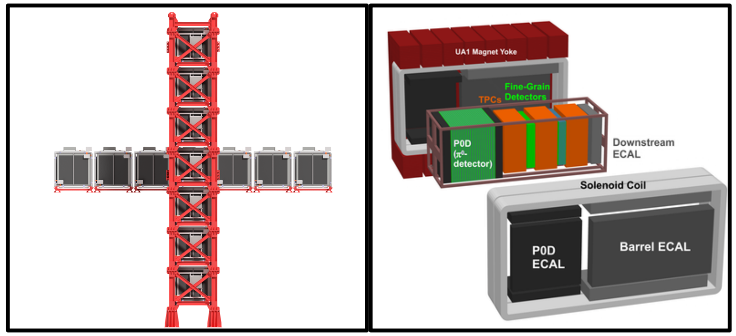


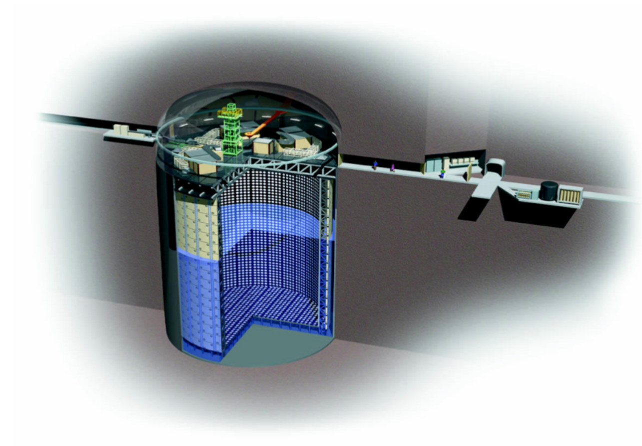
~528 members, 76 Institutes, 14 countries

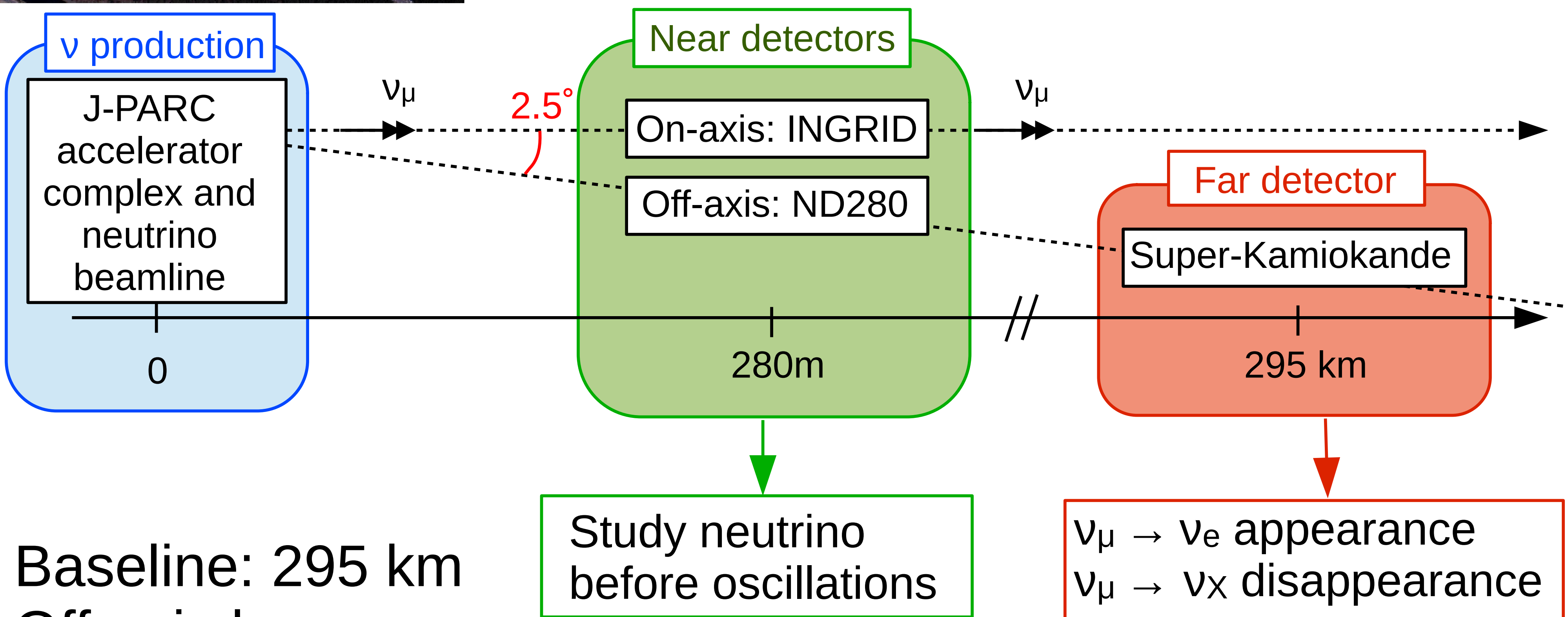
<u>May 2022 dual site collaboration meeting</u>

The T2K experiment
Concept





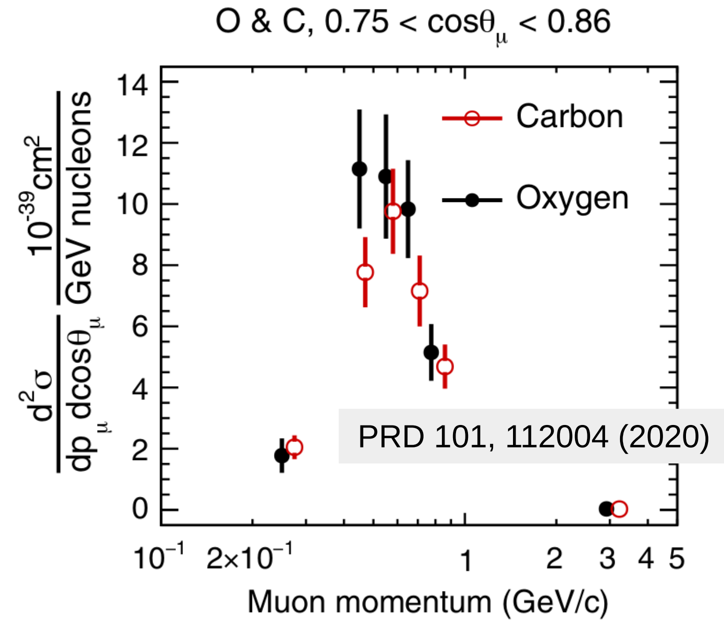




- Baseline: 295 km
- Off-axis beam

The T2K experiment
Physics goals

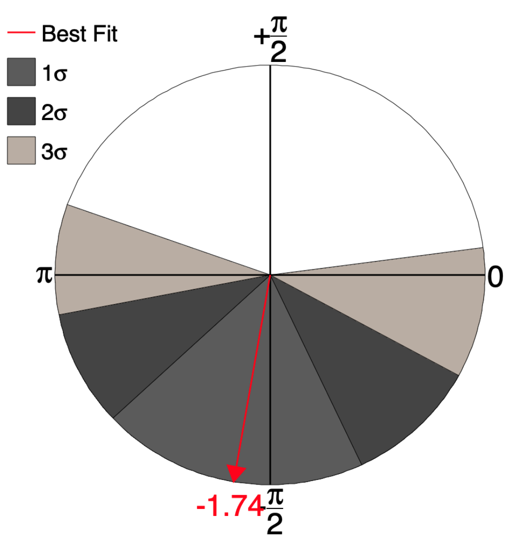
- Neutrino oscillations:
  - Precise measurements of θ_{23} and Δm^2_{32}
  - 3 open questions in standard oscillations
  - Tests of the 3 flavor oscillation model
- Neutrino cross-section measurements



CP symmetry

- difference matter/anti-matter

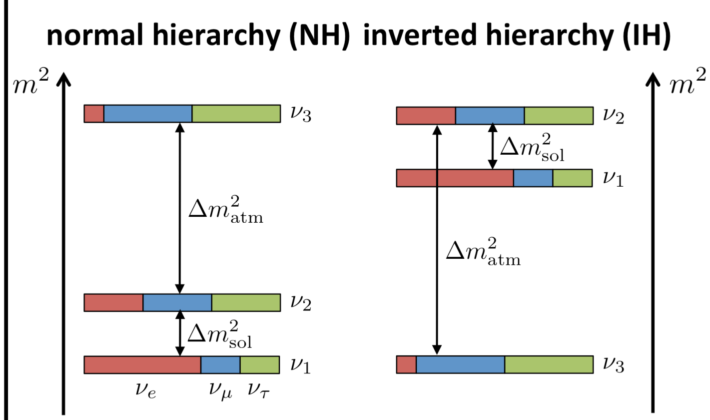
~~CP~~ ⇔ $\sin(\delta) \neq 0$



Nature **580**, 339–344 (2020)

Mass ordering

- Neutrino mass models
- input for other experiments (0νββ, supernova)



Octant of θ_{23}

- symmetries in lepton sector

$\theta_{23}>\pi/4$?

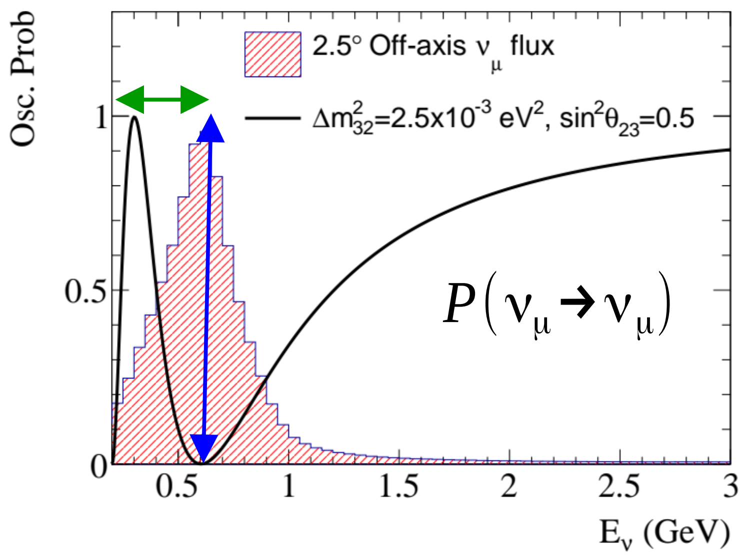
$\theta_{23}=\pi/4$?

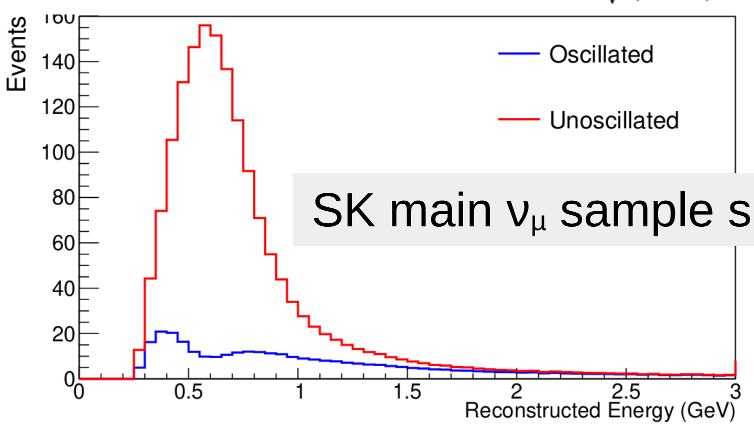
$\theta_{23}<\pi/4$?

Sensitivity to oscillations
Atmospheric parameters

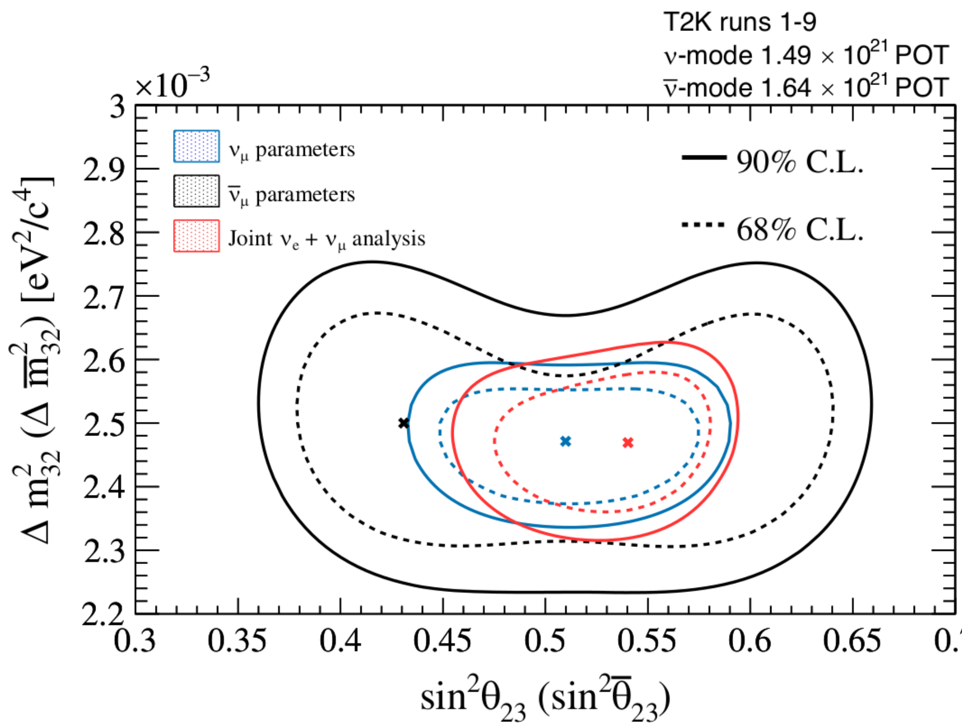
- Muon (anti-)neutrino disappearance gives sensitivity to $\sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$
- θ_{23} octant sensitivity from appearance channel

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \boxed{\sin^2(2\theta_{23})} \sin^2\left(1.27 \frac{\boxed{\Delta m^2} L}{E}\right)$$





$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2(\theta_{23})} \sin^2(2\theta_{13}) \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$$



Phys. Rev. D 103, L011101 (2021)

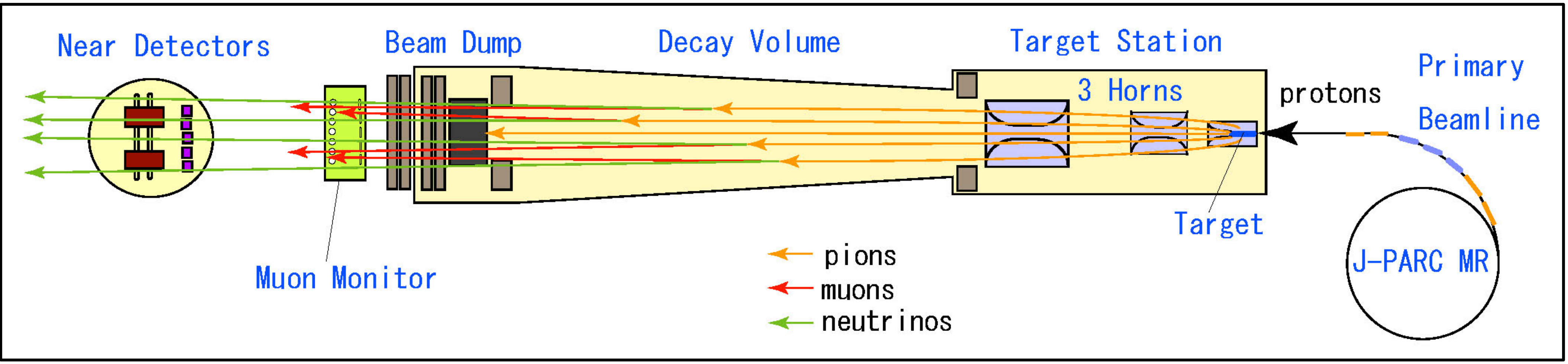
Sensitivity to oscillations
CP violation and mass ordering

- CP phase and mass ordering modify the muon to electron oscillation probabilities, in different ways for neutrinos and anti-neutrinos
- Comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ allows to measure sin(δ) and the mass ordering
- If all other oscillation parameters are well constrained, can also do direct measurements of sin(δ) and MO

Channel	sin(δ) > 0	sin(δ) < 0	Normal ordering	Inverted ordering
$\nu_\mu \rightarrow \nu_e$	Suppressed	Enhanced	Enhanced	Suppressed
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Enhanced	Suppressed	Suppressed	Enhanced

- Degeneracies between the effect of δ and the mass ordering
- T2K baseline “not very long”: effect of δ dominates (~<27% vs ~10%)

Neutrino production
Conventional neutrino beam

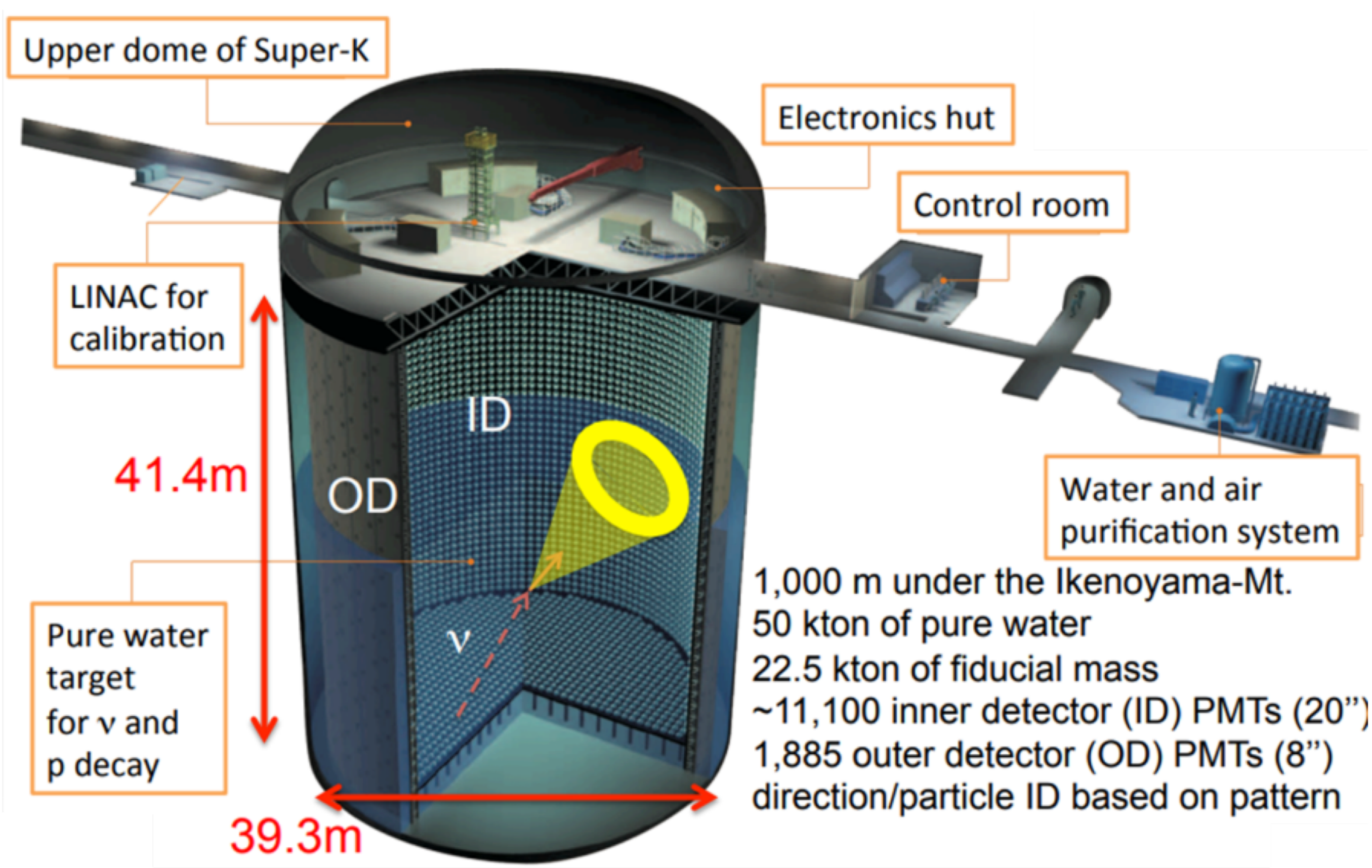


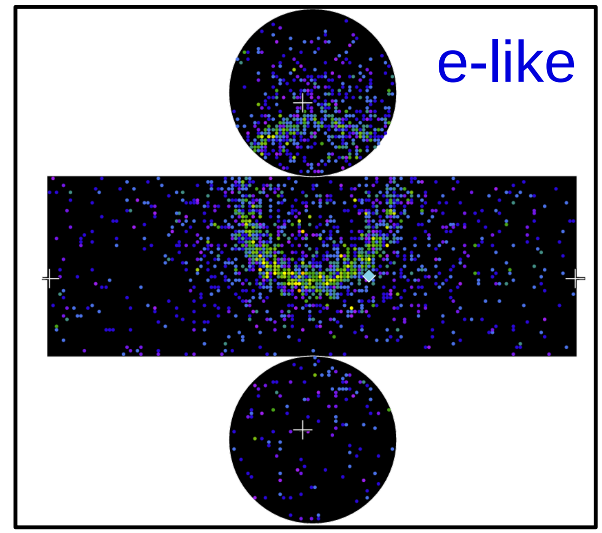
Almost pure $\nu_\mu/\bar{\nu}_\mu$ beam, with an intrinsic $\nu_e/\bar{\nu}_e$ component (<1% at peak)

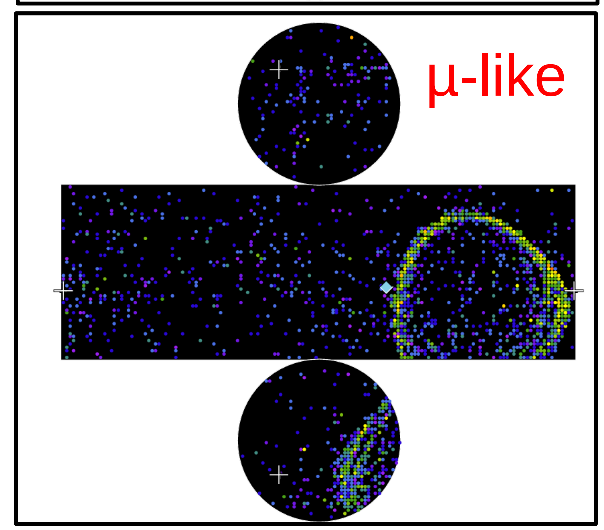
Can switch from ν_μ beam to $\bar{\nu}_\mu$ beam by inverting the horn polarities

Far detector
Super-Kamiokande

- Good separation between $\mu^{\pm}$ and $e^{\pm}$ (**separate ν_μ and ν_e** CC interactions)
  → Less than 1% mis-PID at 1 GeV for single ring events
- Cannot separate ν and $\bar{\nu}$ on an event by event basis
- Only sees photons and charge particle above Cerenkov threshold



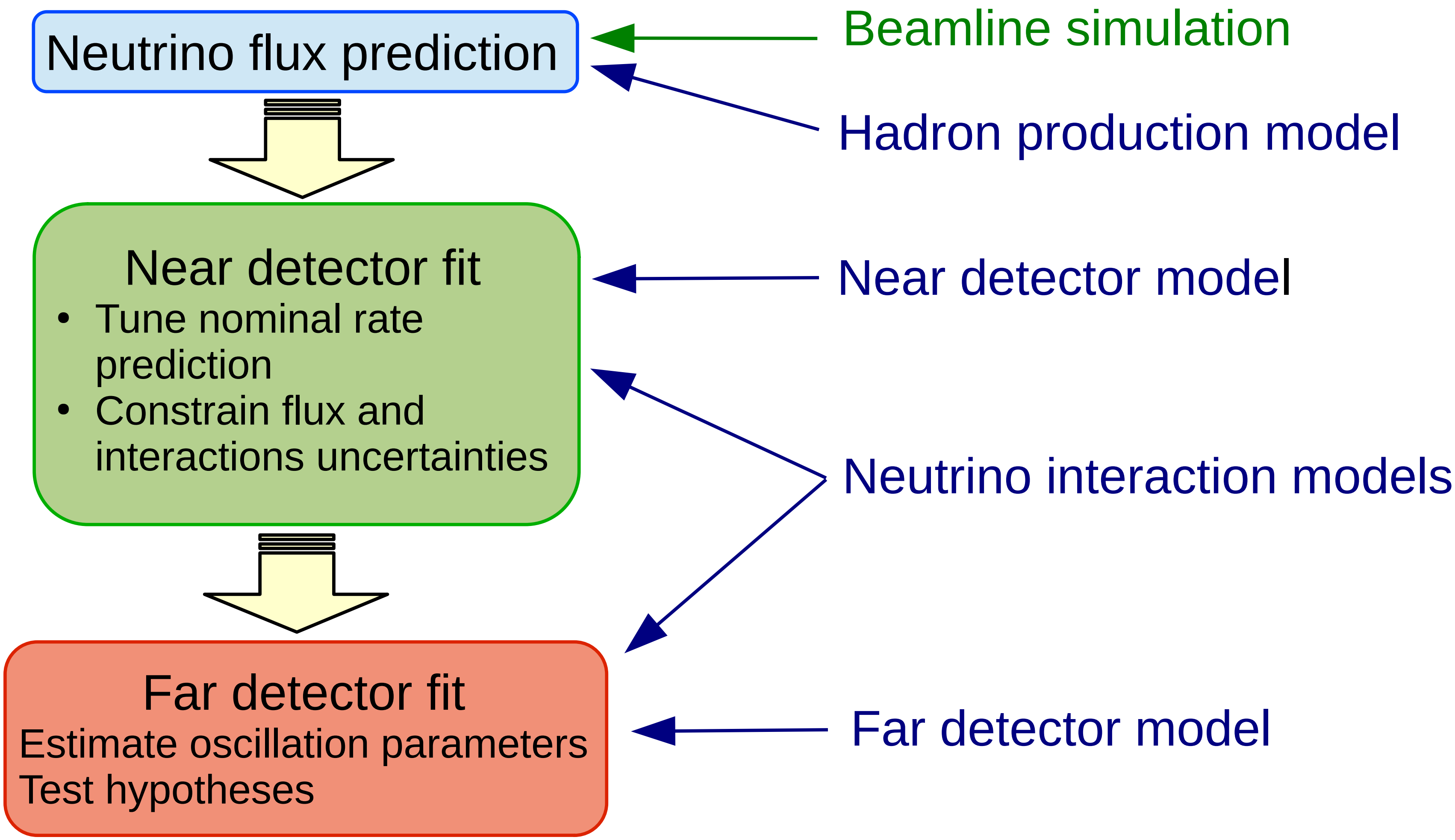




New oscillation result

Oscillation analysis
Overview

- Likelihood analysis: compare observed data at the far detector to predictions based on a model of the experiment to make measurements
- Produce both frequentist and Bayesian results



Near and far detector fits done sequentially or simultaneously depending on analysis

New analysis overview

Re-analysis of the data set used for Neutrino 2020 result, with significant improvements on all parts of the analysis

Flux prediction

- Use of NA61/SHINE 2010 replica target data for hadron production
- Updated model for cooling water flow in horns
- Analysis improvements for non-hadronic uncertainties

Neutrino interaction model

- Improved uncertainties for spectral function model
- Additional uncertainties for resonant and multi-pion events, as well as final state interactions

Near detector analysis

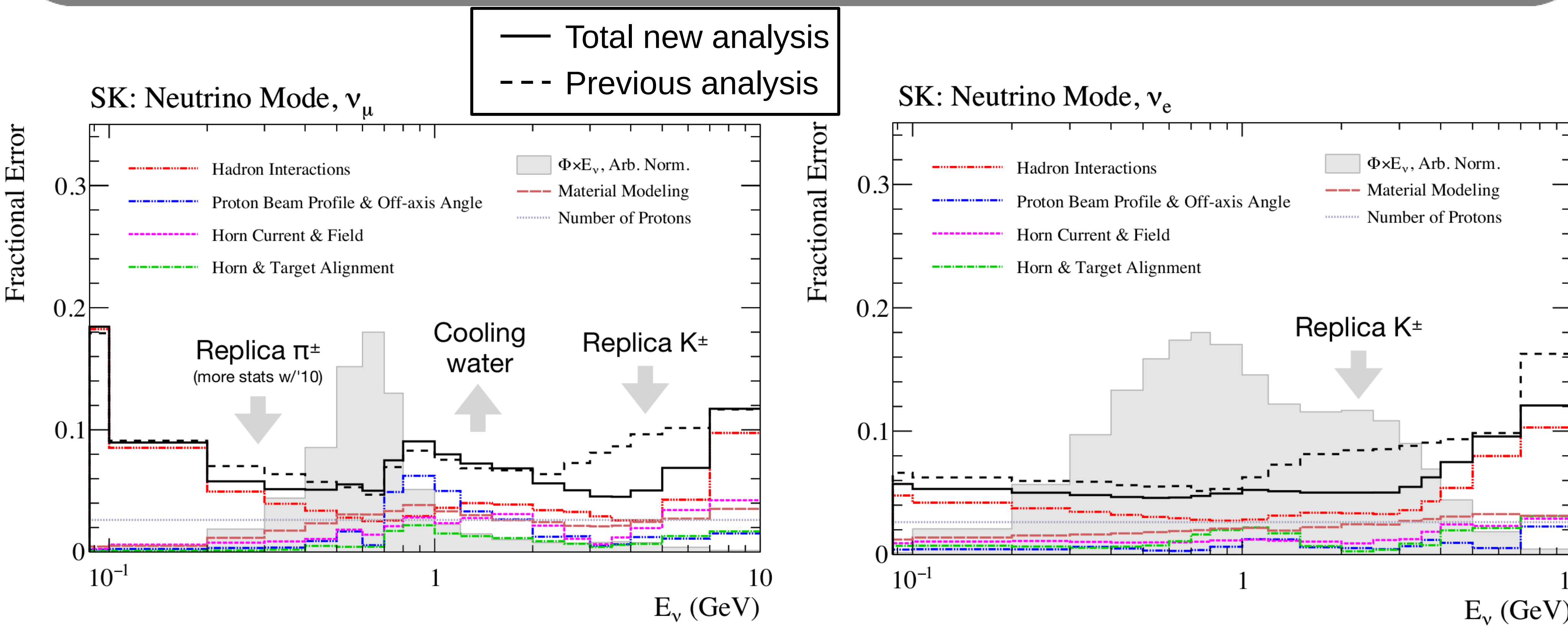
- Use of proton tagging for CC0π events
- First use of ECAL in oscillation analysis, to tag photons

Far detector analysis

- New μ-like CC1π sample
- First use of multi-ring events in T2K

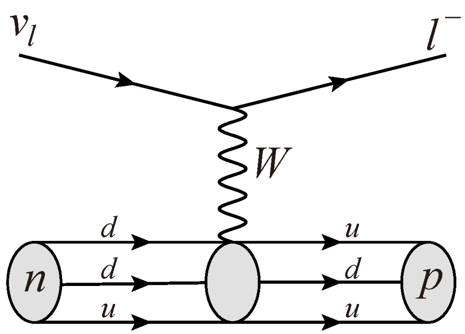
Neutrino flux prediction Update

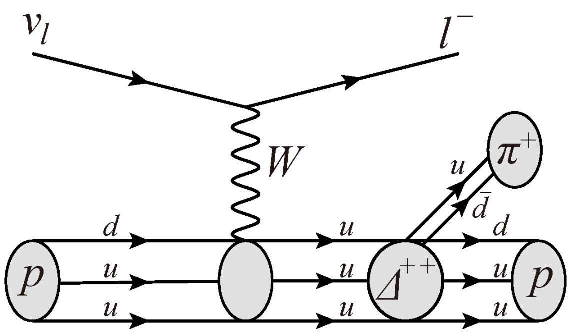
- Dominant uncertainty: hadron production in collisions of protons on graphite target
- Simulation tuned based on hadron multiplicity measurements by NA61/SHINE
- Moved from using 2009 T2K replica target measurement (Eur. Phys. J. C76, 617) to 2010 one (Eur. Phys. J. C79, 100):
  - ➔ more statistics for $\pi^{\pm}$ production
  - ➔ adds $K^{\pm}$ and proton data
- Additional updates on other part of the models, in particular cooling water flow in horns



Neutrino interaction model

- At T2K energies, dominant interaction mode is CCQE
- Significant "2p2h" (multinucleon) and resonant contributions.
  - Can mimic the primary signal at SK, causing a bias in E_ν reconstruction
- New for this analysis:
  - Continued development of the CCQE and 2p2h models
  - Renewed development the resonant model
  - Improvements to multi-pion production and final state interaction model





CCQE

Based on the **Spectral Function model**

- Empirical uncertainties replaced with more theory-driven alternatives
- New uncertainties on nuclear shell structure, nuclear potential and Pauli Blocking
- Nucleon removal energy has a parameterized dependence on momentum transfer

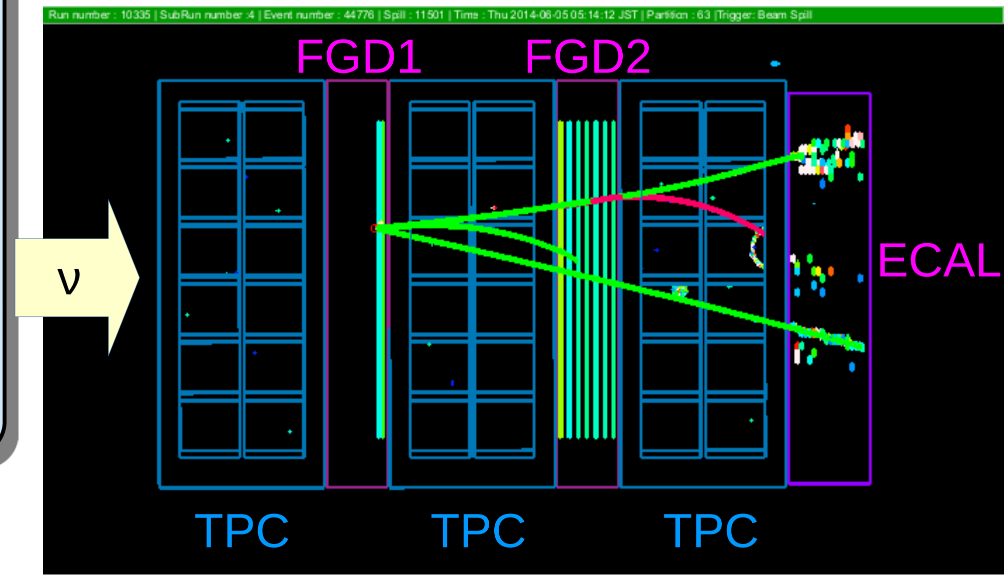
CC resonant

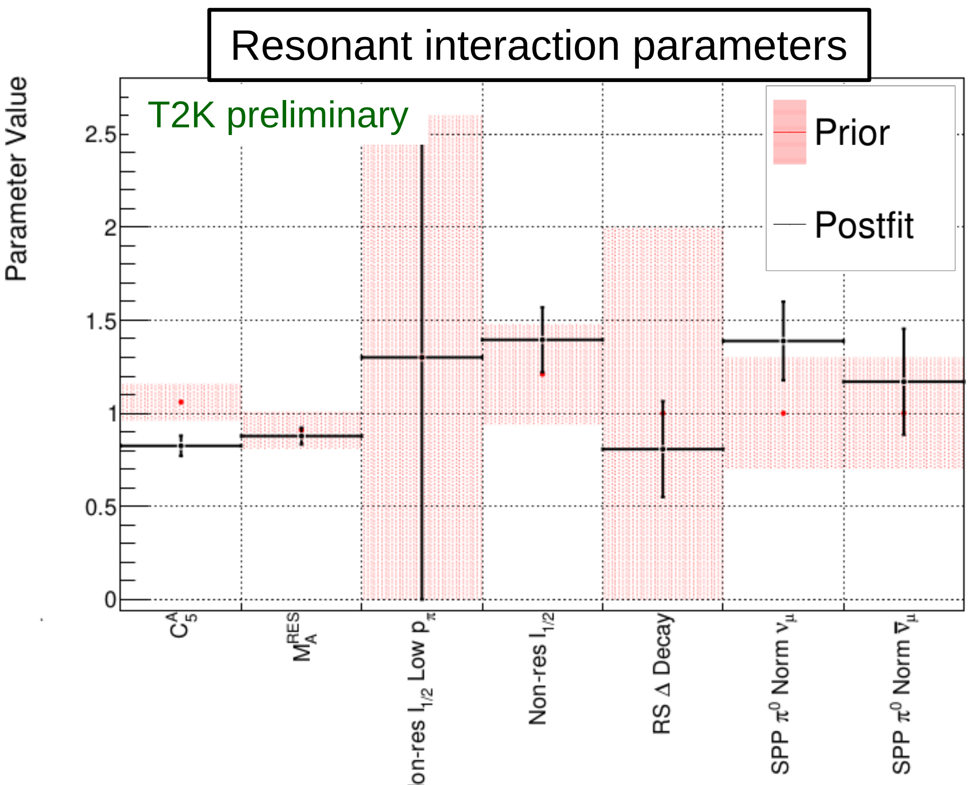
Based on the **Rein–Sehgal (RS) model** with **RFG nuclear model**

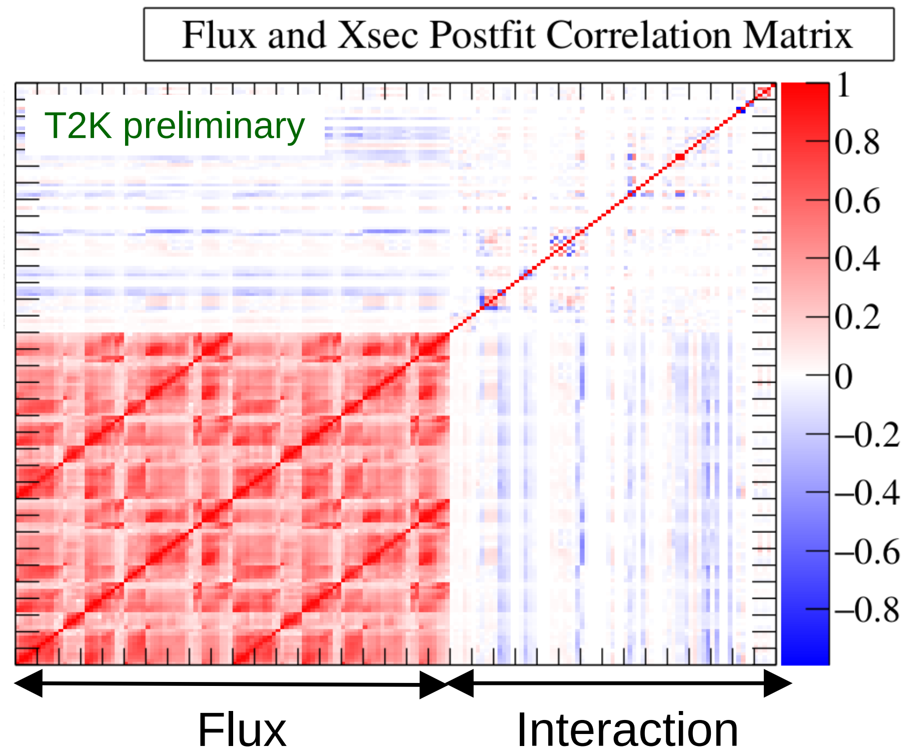
- New bubble chamber tune of RS parameters
- New resonance decay uncertainties
- Effective inclusion of binding energy
- New uncertainty in $\pi^\pm$ vs π^0 production

Near detector fit

- Select CC ν_μ interactions in one of the 2 Fine Grained Detectors
- Separate events by running mode, FGD (FGD1: CH, FGD2: CH+$H_2$0) and observed particles ($\pi^\pm$, γ, p)
- Additional samples in $\bar{\nu}$-mode to constrain wrong sign background
- Fit gives tuned nominal values and constrained uncertainties for flux and interaction parameters



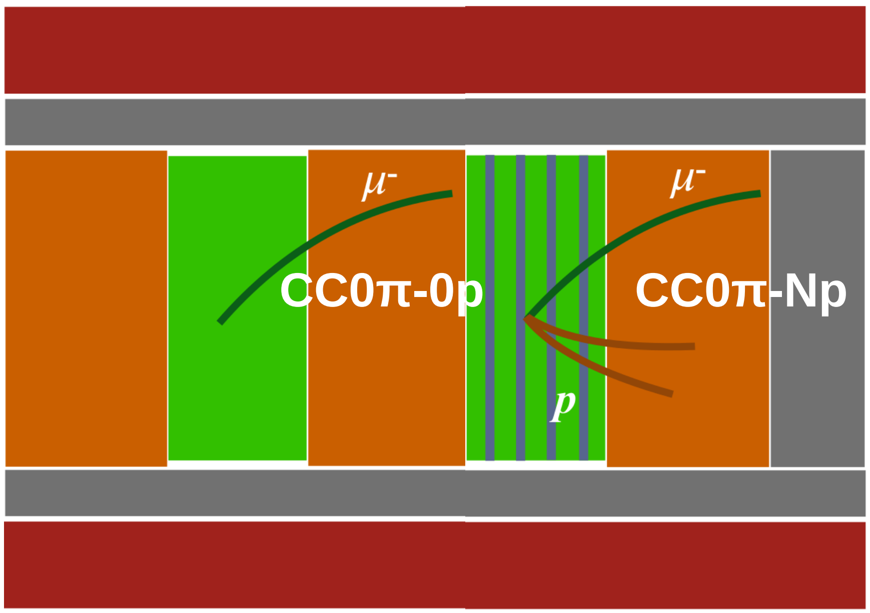




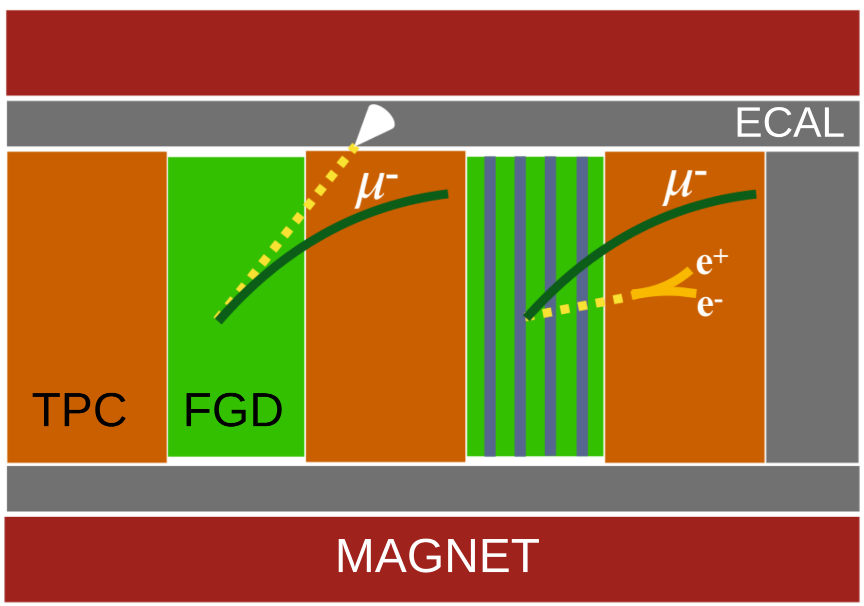
New ND fit p-value: 0.109 (>5% threshold)

Near detector fit Update

- Changes to the ν-mode samples:
  - Split CC0π sample based on presence or absence of proton
  - Separate events with tagged photons
- Selections for $\bar{\nu}$-mode samples unchanged
- Total number of ND samples 18 → 22



Different fractions of reactions and selects different parts of the phase space
→ Increased ability to constrain CCQE and 2p2h models



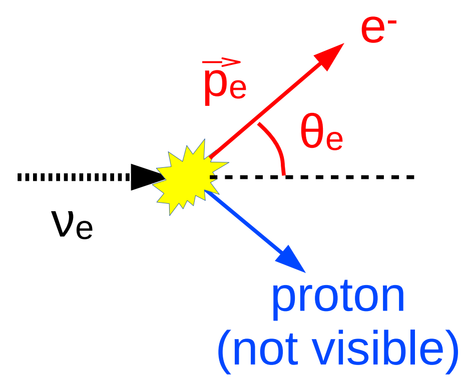
- Creates new sample dominated by DIS and resonant $CC\pi^0$
- Increased purity for other (CC0π and CC1π) samples

Far detector samples
Single ring samples

- At T2K energies, only photons, leptons and pions visible in SK
- Good energy estimator for 2 body-like interactions from lepton momentum and angle
- Nominal event selection targets CCQE events, by selecting events with a single particle (=lepton) visible (“single ring”)
- Events separated by neutrino mode and lepton flavor
- One additional sample in ν-mode targets CC1π ν_e events, tagging Michel electron from pion decay

$\nu + n \rightarrow p + l^-$

$\bar{\nu} + p \rightarrow n + l^+$

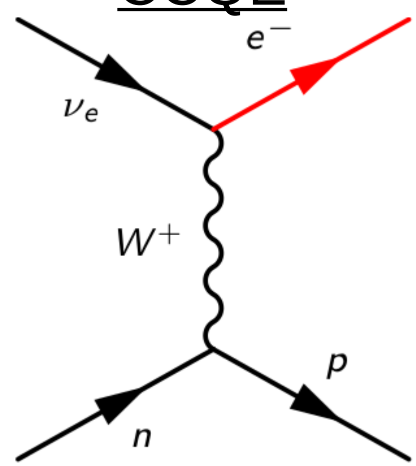


5 single ring samples

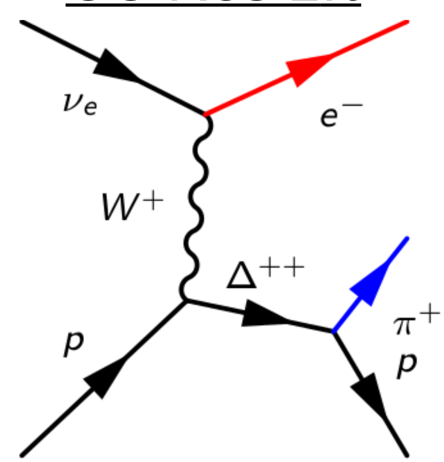
	e-like	μ-like
ν-mode	1Re + 0 M.e	1Rμ + 0/1 M.e
	1Re + 1 M.e	
$\bar{\nu}$-mode	1 Re + 0 M.e	1Rμ +0/1 M.e

M.e = Michel electron

CCQE

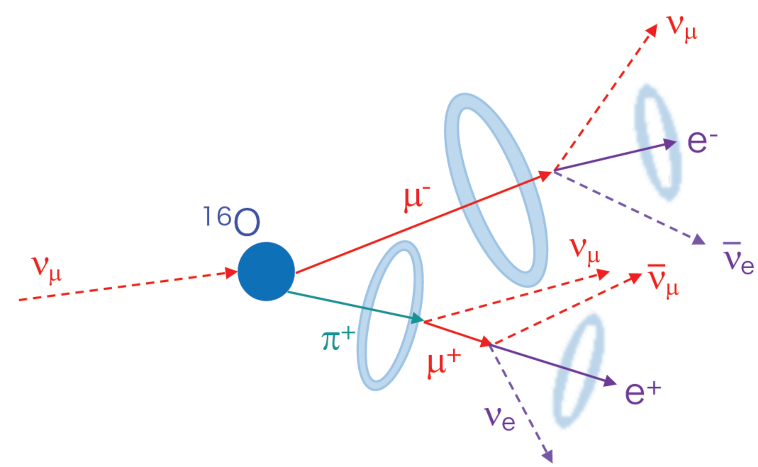


CC Res 1π+

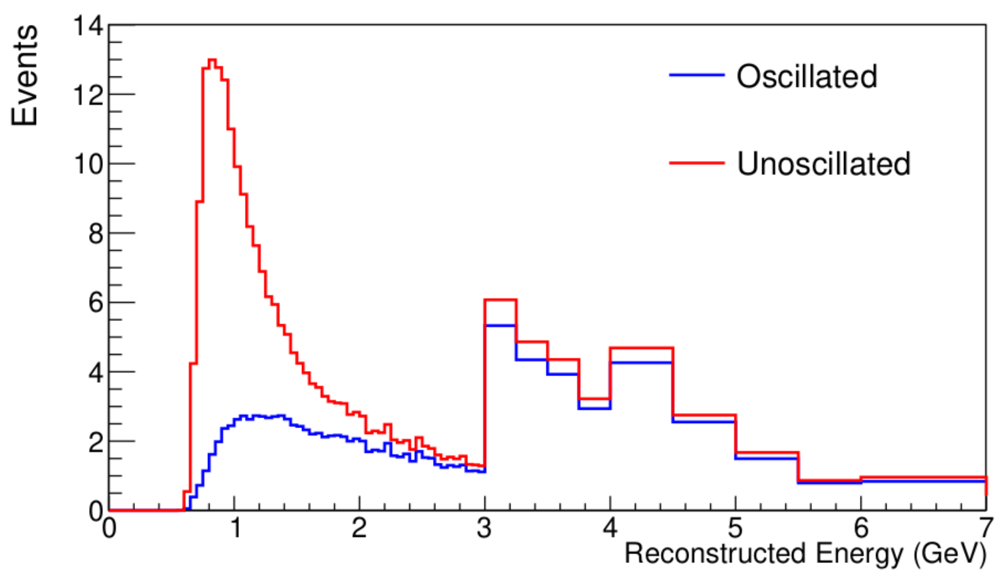


Far detector samples
New sample

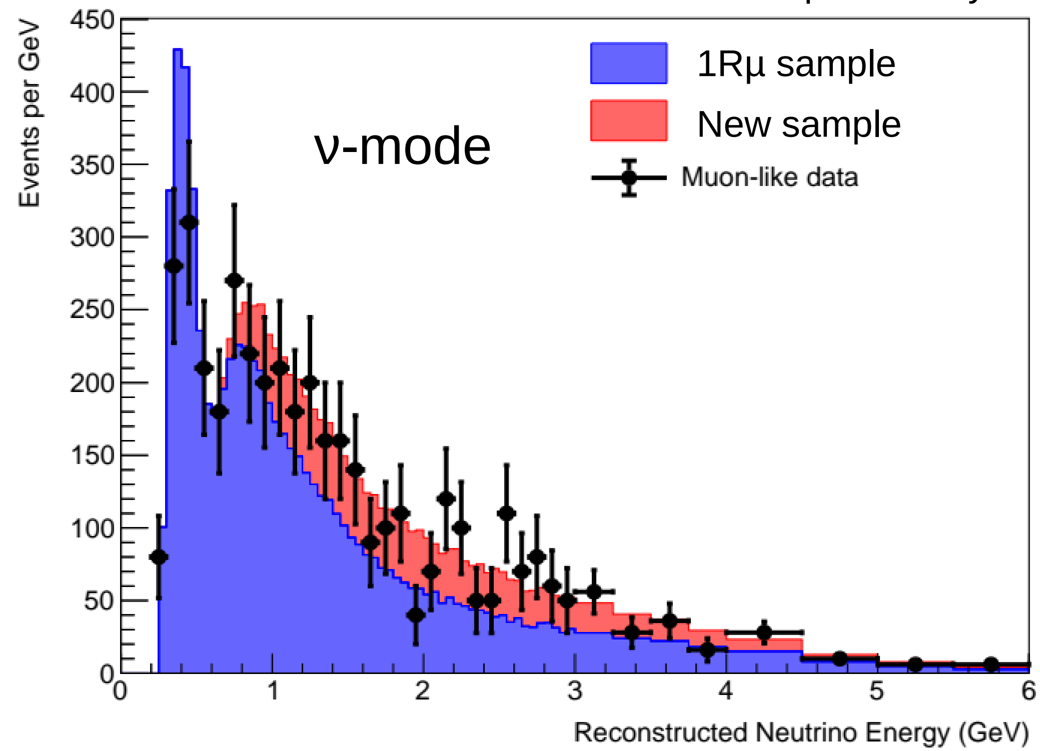
- New analysis adds a far detector sample targeting ν_μ CC1π^+ interactions in ν-mode
- Combination of 1Rμ + 2 M.e and 2 rings events
- Increase ν-mode μ-like statistics by ~30%
- Sensitive to oscillations, but higher energy than nominal μ-like sample
- Dominated by different interaction mode



First use of multi-ring events in T2K

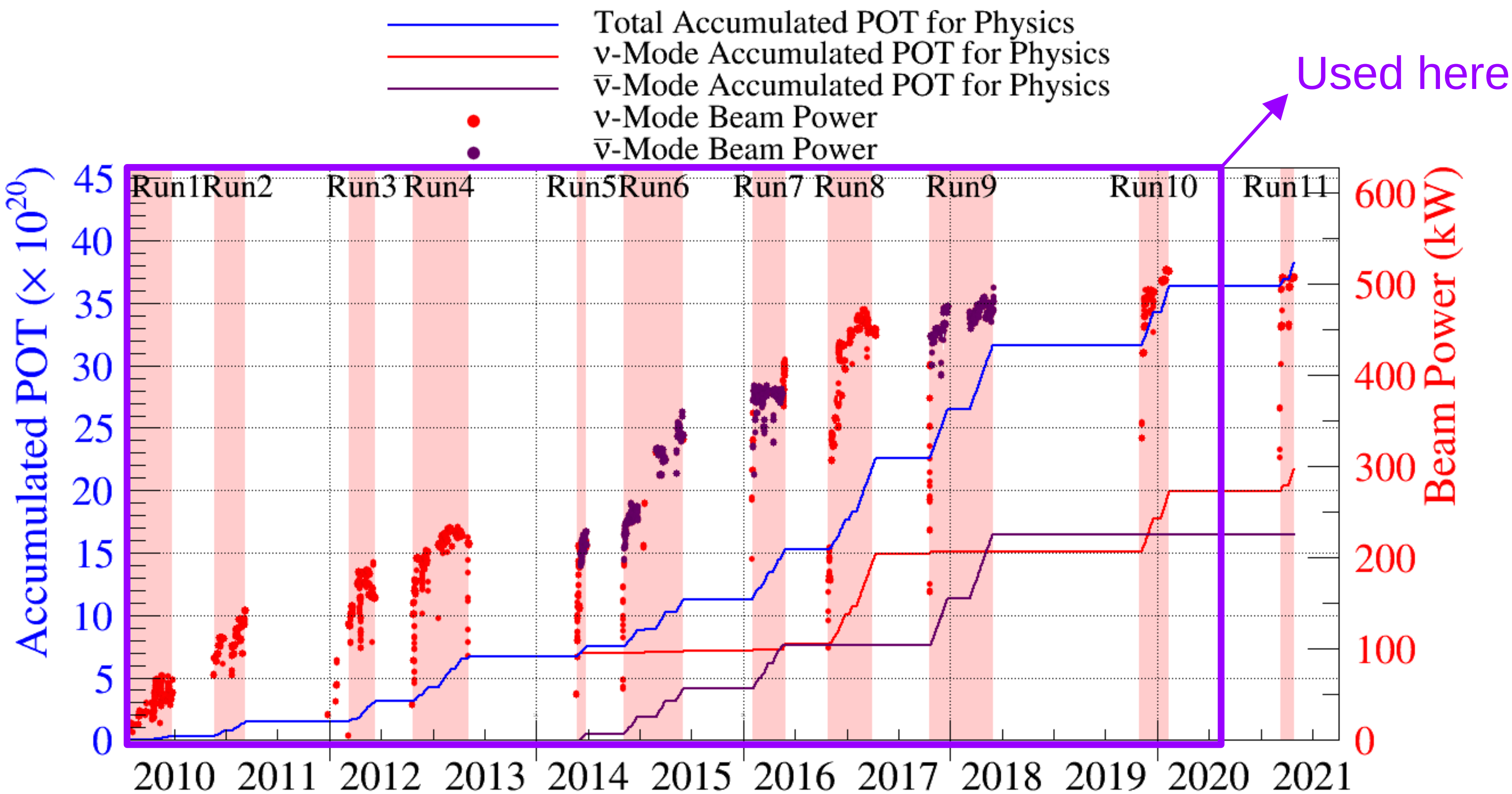


T2K preliminary



Data set

- New result uses same data set as neutrino 2020 result: “Run 1-10”
- One more year of data available and not used yet: “Run 11”



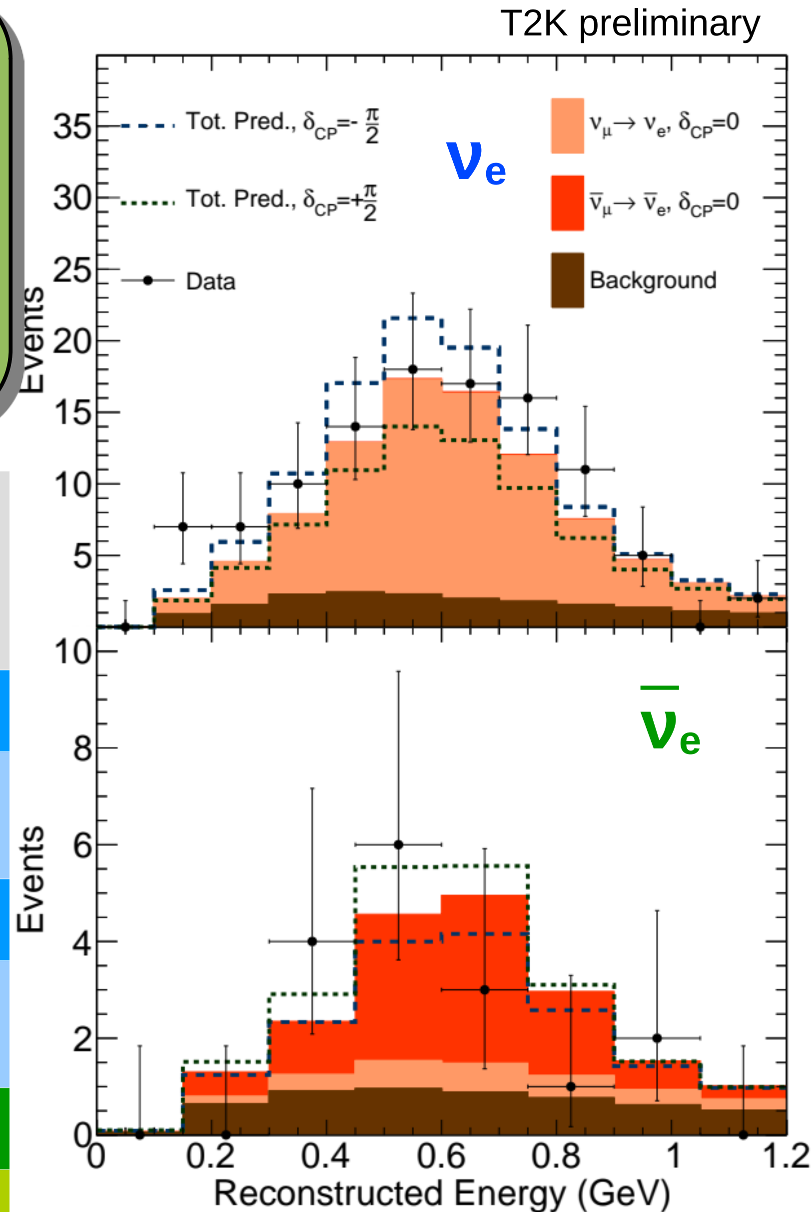
Used here:

Near detectors	**Far detector**
ν-mode: 1.3905 x 10^{21} POT	ν-mode: 1.9664 x 10^{21} POT
$\bar{\nu}$-mode: 0.6307 x 10^{21} POT	$\bar{\nu}$-mode: 1.6346 x 10^{21} POT

Far detector samples
Data set

- Numbers of observed e-like events indicate a preference for sin(δ)<0
- Less events than predicted for ν-mode 1Rμ sample
- Goodness of fit p-value for this sample of 0.04 (rate only) and 0.35 (rate+shape)
- Considering look-elsewhere-effect, above our 5% threshold

Mode	Sample	δ=-π/2 MC	δ=0 MC	δ=π/2 MC	δ=π MC	Data
ν	1Re	102.7	86.7	71.1	87.1	**94**
	1Re CC1π$^+$	10.0	8.7	7.1	8.4	**14**
	1Rμ	379.1	378.3	379.1	380.0	**318**
	MRμ CC1π$^+$	116.5	116.0	116.5	117.0	**134**
$\bar{\nu}$	1Re	17.3	19.7	21.8	19.4	**16**
	1Rμ	144.9	144.5	144.9	145.3	**137**

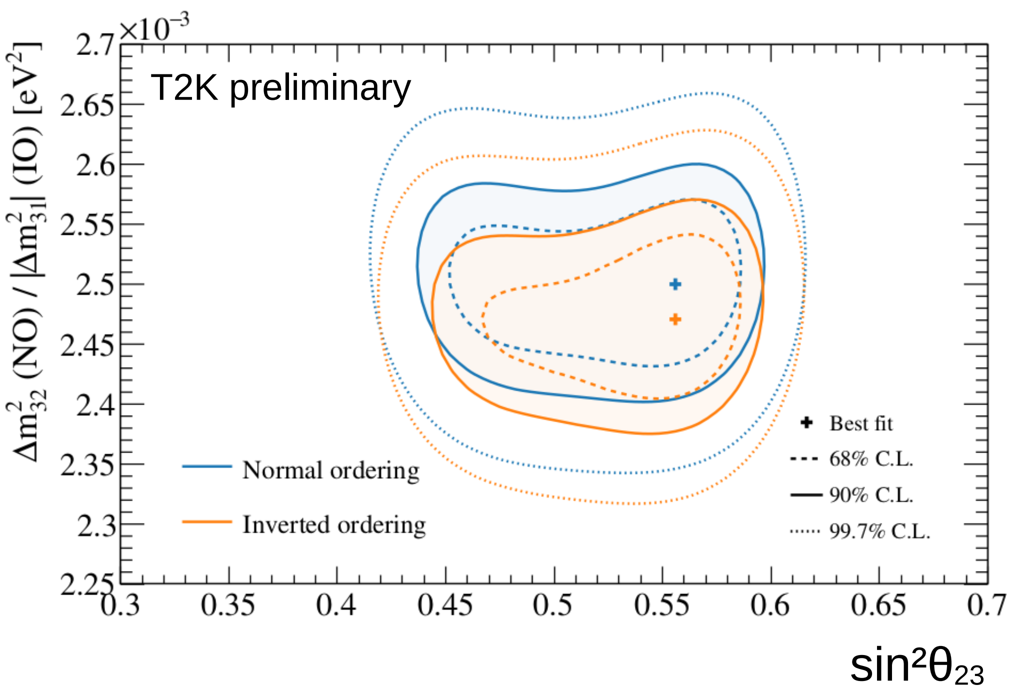


MC: $\sin^2(\theta_{23})=0.561$, $\Delta m^2_{32}=2.494 \times 10^{-3}$ eV^{2}c^{-4}, $\sin^2(\theta_{13})=0.0220$, Normal ordering

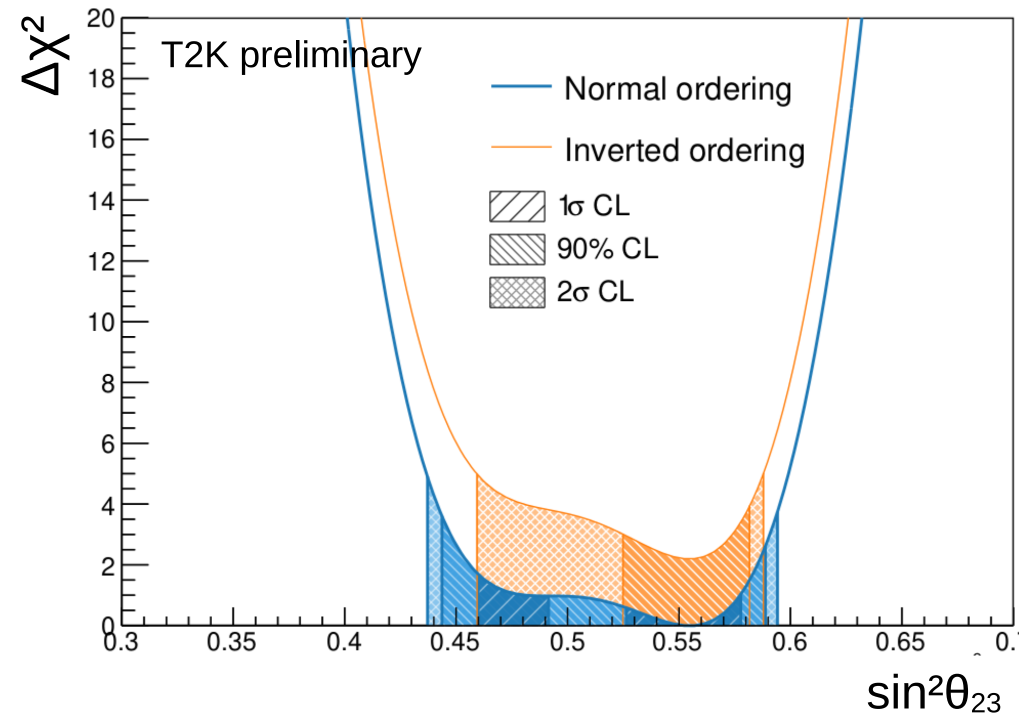
New oscillation result
Atmospheric parameters

- Best fit in the upper octant
- Lower octant still allowed at the 68% CL level
- Additional Gaussian smearing ($\sigma = 0.027 \times 10^{-3}$ eV²/c⁴) in Δm^2 from results of potential bias studies using alternative neutrino interaction models

2D constant $\Delta\chi^2$ regions



1D frequentist intervals for $\sin^2\theta_{23}$
(Feldman-Cousins method)

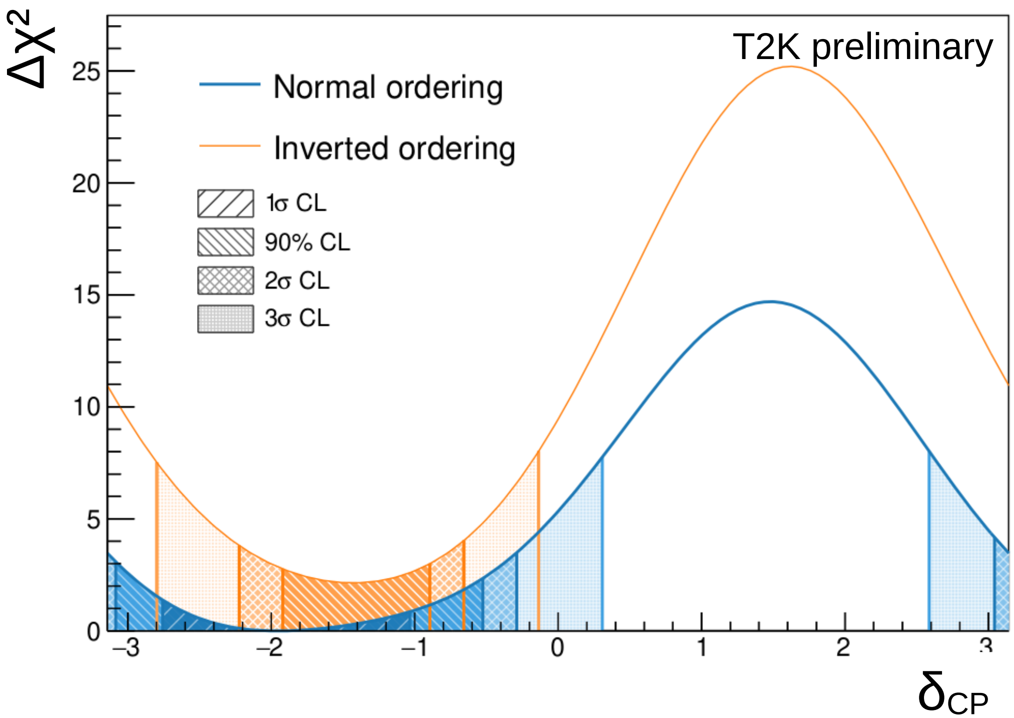


Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

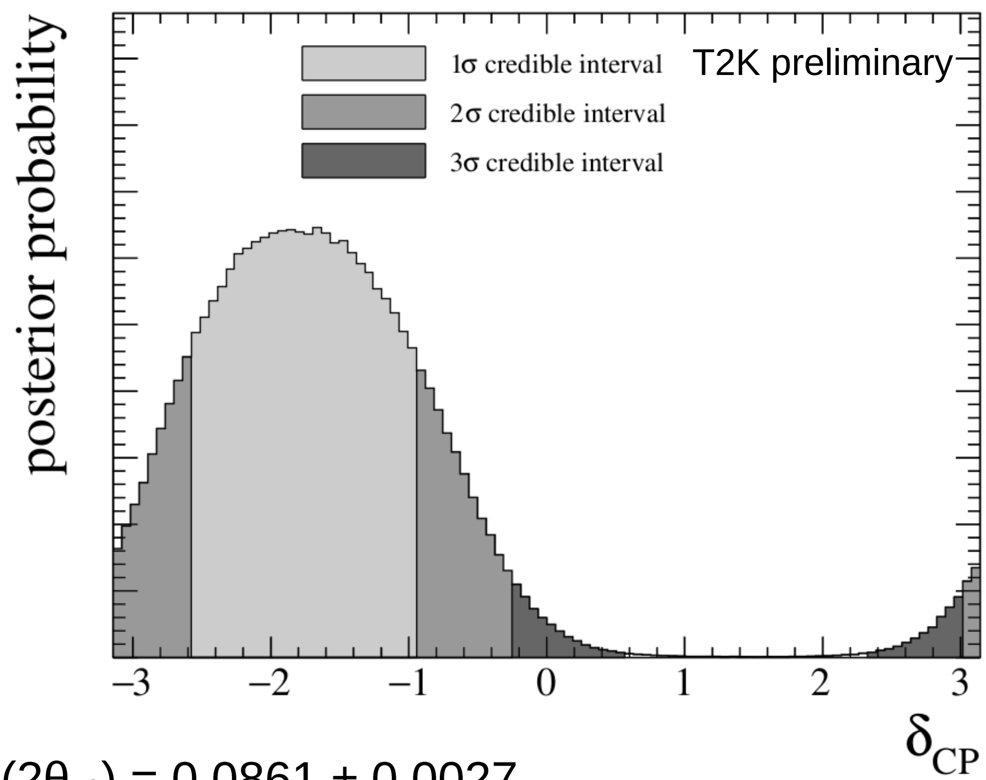
New oscillation result
CP phase

- CP-conserving values of δ=0 and δ=π outside of 90% CL intervals
- Tested effect of alternative interaction model, did not find biases that would change this conclusion

Frequentist results
(Feldman-Cousins method)



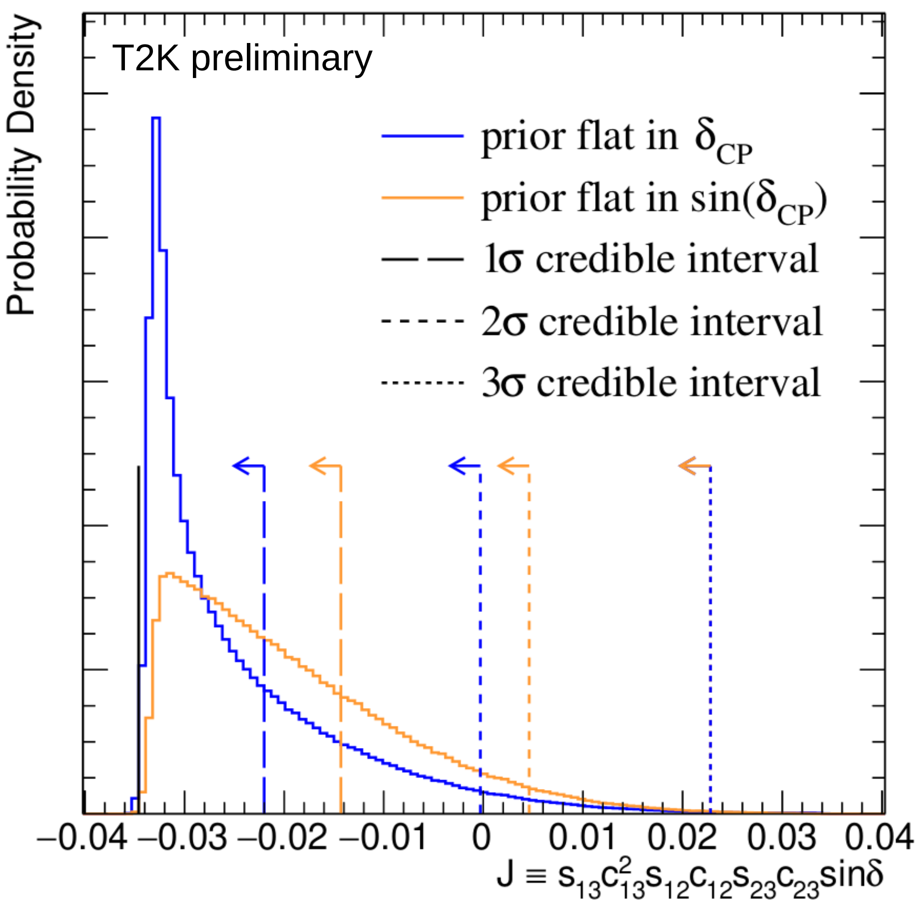
Bayesian results
(marginalized over MO)

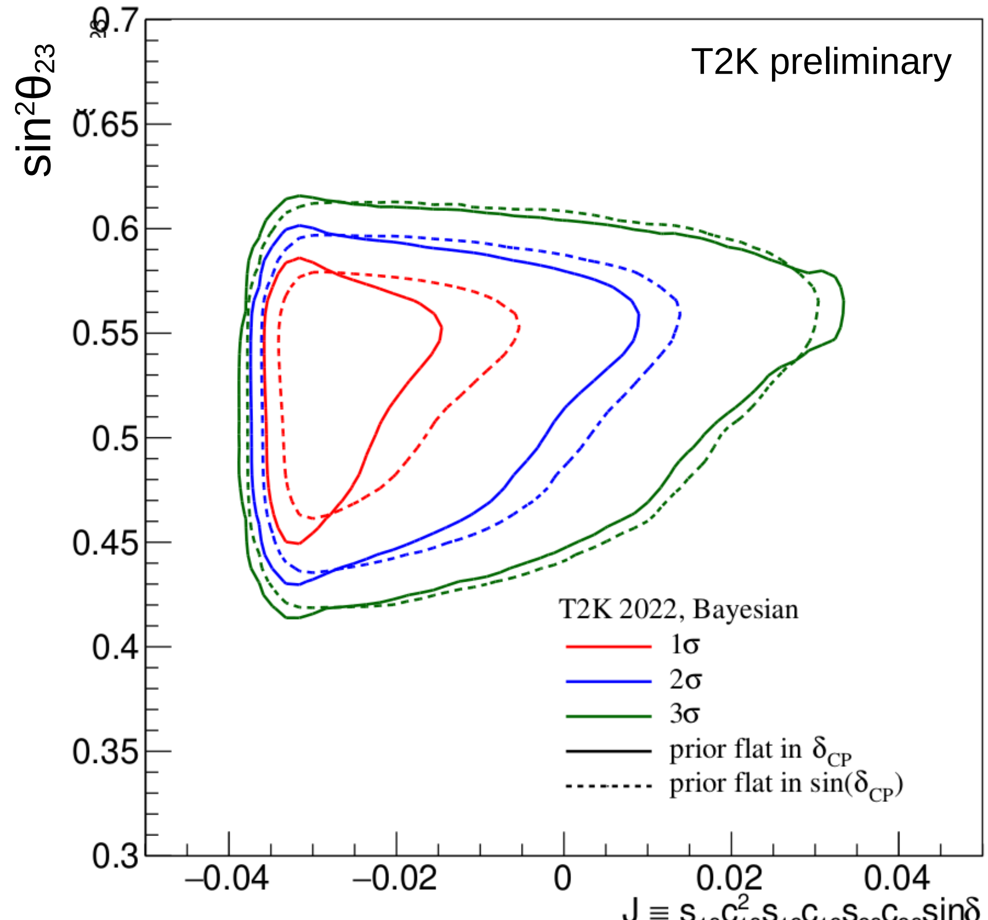


Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

New oscillation result
Jarlskog invariant

- Can search for potential CP violation by looking at the posterior probability and credible intervals for J_{CP}
- Results depend on the metric in which we assume the prior for δ to be uniform





Marginalized over mass ordering hypotheses
Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

New oscillation result
Model preference

- Looking at posterior probabilities for the different combinations of octant and mass ordering hypotheses
- Mild preference for normal ordering and upper octant, stronger when using constraint from reactor experiments for θ_{13}, but still limited significance

T2K only

T2K preliminary	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO $(\Delta m^2_{32} > 0)$	0.24	0.39	0.63
IO $(\Delta m^2_{32} < 0)$	0.15	0.22	0.37
Sum	0.39	0.61	1.00

T2K+reactor θ_{13}

T2K preliminary	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO $(\Delta m^2_{32} > 0)$	0.20	0.54	0.74
IO $(\Delta m^2_{32} < 0)$	0.05	0.21	0.26
Sum	0.25	0.75	1.00

θ_{13} constraint from reactor experiments is $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

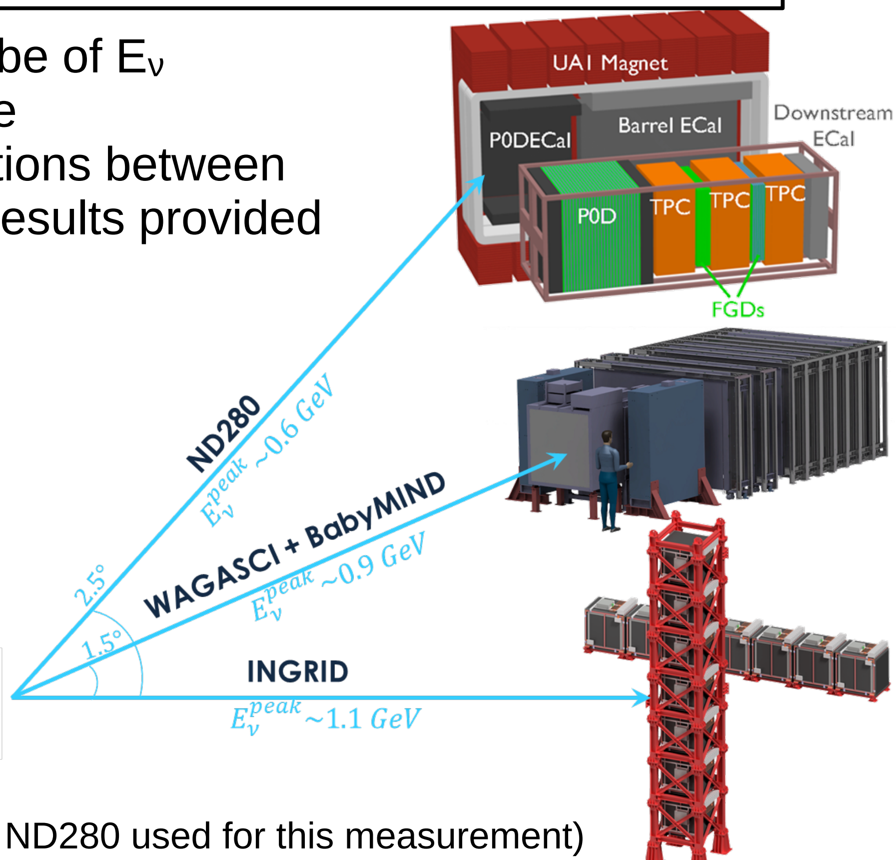
Cross-section and interaction measurements highlights

New ND280 measurements

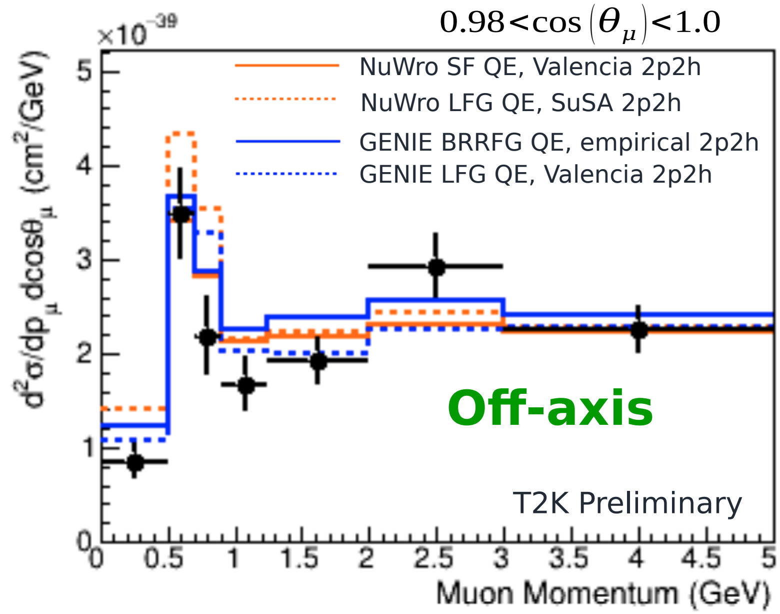
- Many new results since NEUTRINO 2020
- Particular focus on “joint” measurements (e.g. C/O, $\nu_\mu/\bar{\nu}_\mu$, on/off axis)
- Direct probes of physics most relevant to oscillation analyses
- Also perform challenging low rate measurements (CC coherent on C)

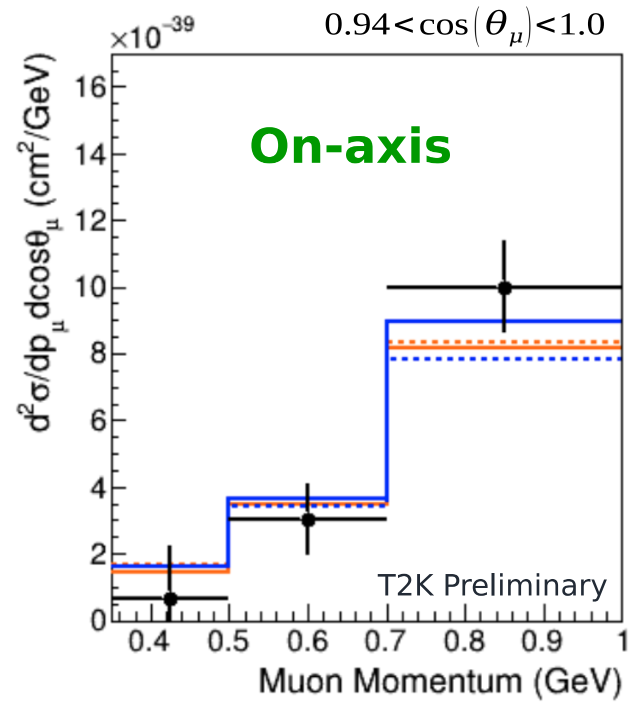
Joint On/Off axis measurements

- A direct probe of E_ν dependence
- Full correlations between on/off axis results provided



(only INGRID and ND280 used for this measurement)

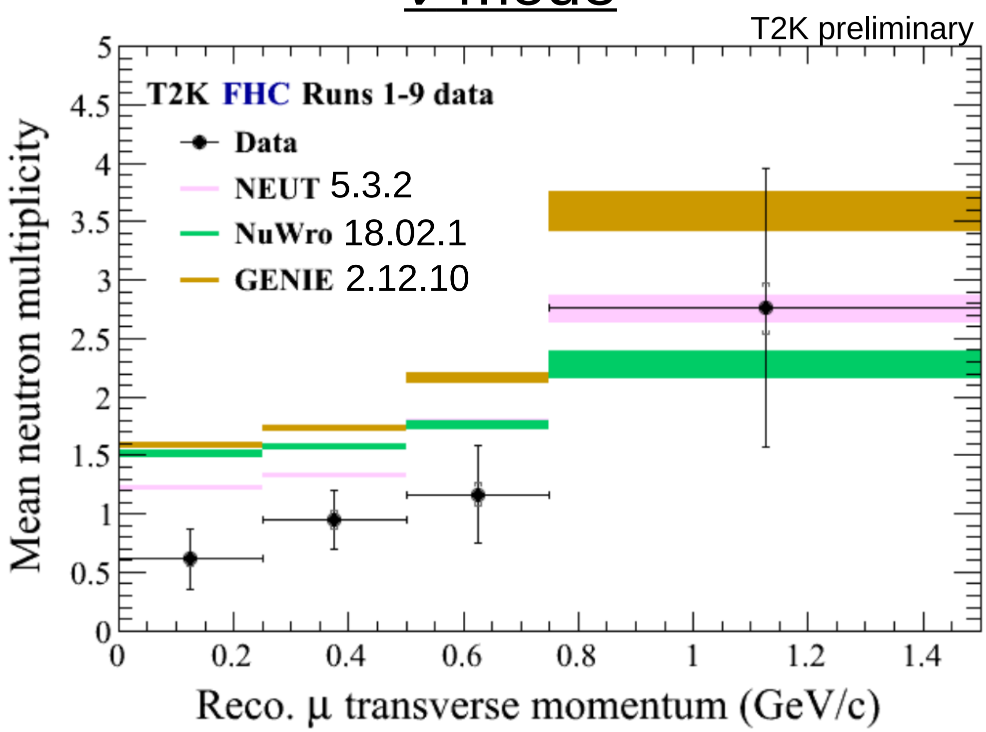




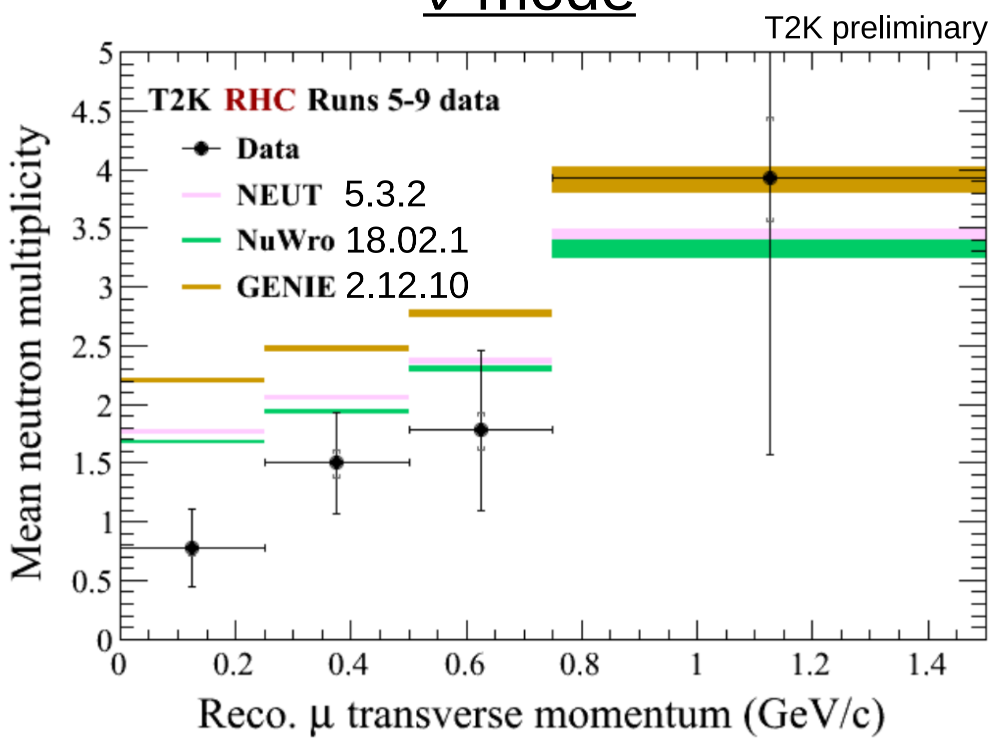
Neutron multiplicities at Super-K

- Use of neutron tagging interesting in water Cerenkov detectors to separate $\nu/\bar{\nu}$, CC/NC ν interaction and reject backgrounds
- Use in analysis requires good ability to predict neutron productions in neutrino interactions, taking into account final state and secondary interactions
- Using neural network based tagging algorithm, compared number of neutrons observed in μ-like samples for oscillation analysis (old analysis, run 1-9 = neutrino 2018) to predictions
- All generator considered found to over-predict neutron production

ν-mode



$\bar{\nu}$-mode



Future

T2K-NOvA joint analysis

- 2 long baseline experiments with different baselines, energy ranges and detector technologies: complementarity to study oscillations
- The two collaborations have started work on a joint analysis of their data
  - ➔ increased sensitivity
  - ➔ ability to break degeneracy between mass ordering and δ_{CP}

Experimental Property	T2K	NOvA
Proton Beam Energy	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection Technology	Water Cherenkov	Segmented liquid sintillator bars
CP Effect*	32%	22%
Matter Effect	9%	29%

*Minimum difference of $\sin(\delta_{cp})=0$ and $\sin(\delta_{cp})=\pm1$, neutrinos and antineutrinos

T2K-SK atmospheric joint analysis

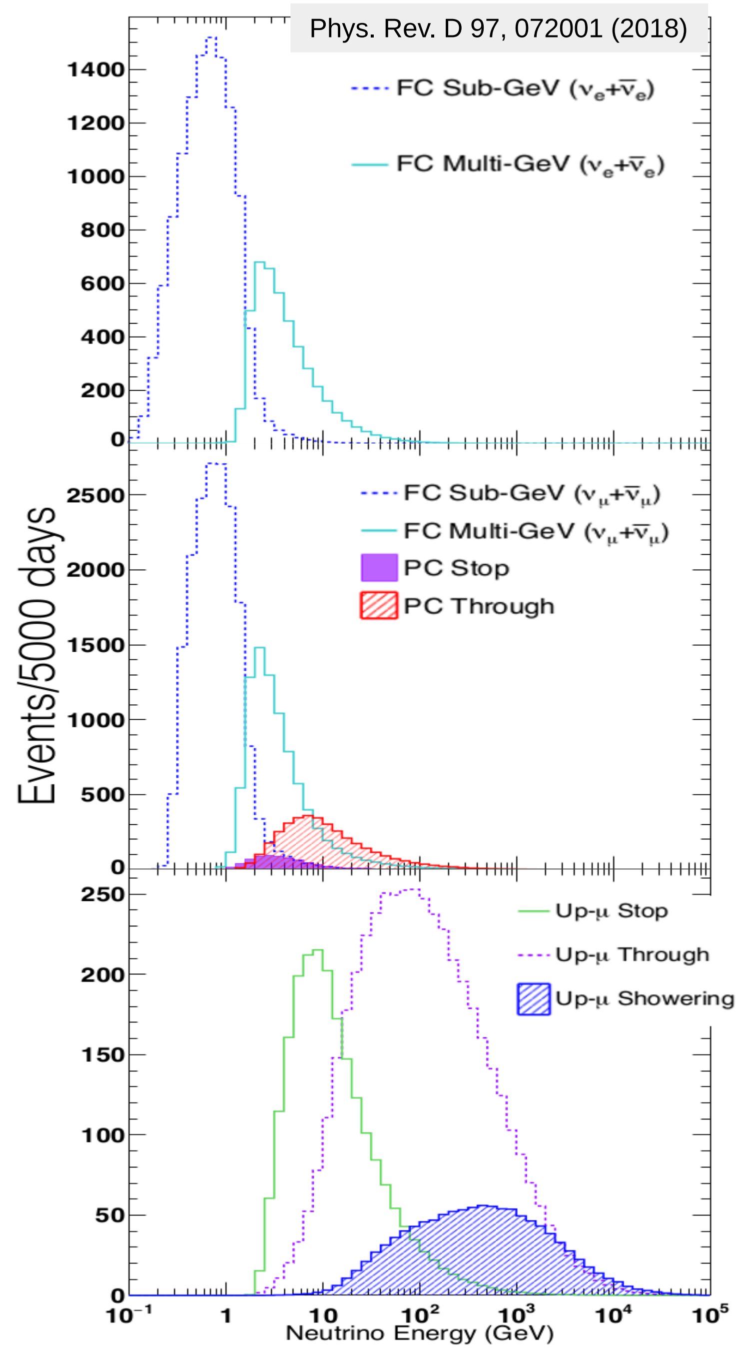
- Second (separate) joint fit in preparation with Super-Kamiokande atmospheric data
- Common detector between the two experiments: need to check effect of correlations between systematics
- Super-K atmospheric covers wider range of energies and baseline than T2K, with in particular sensitivity to MO from high energy neutrinos
- Produced sensitivity studies for the common analysis

Based on older analyses than shown at this conference (modified to build a coherent analysis)

- T2K: neutrino 2020 analysis
- Super-K: SK-IV fiTQun analysis (Prog. Theor. Exp. Phys. 2019, 053F01)

Model used

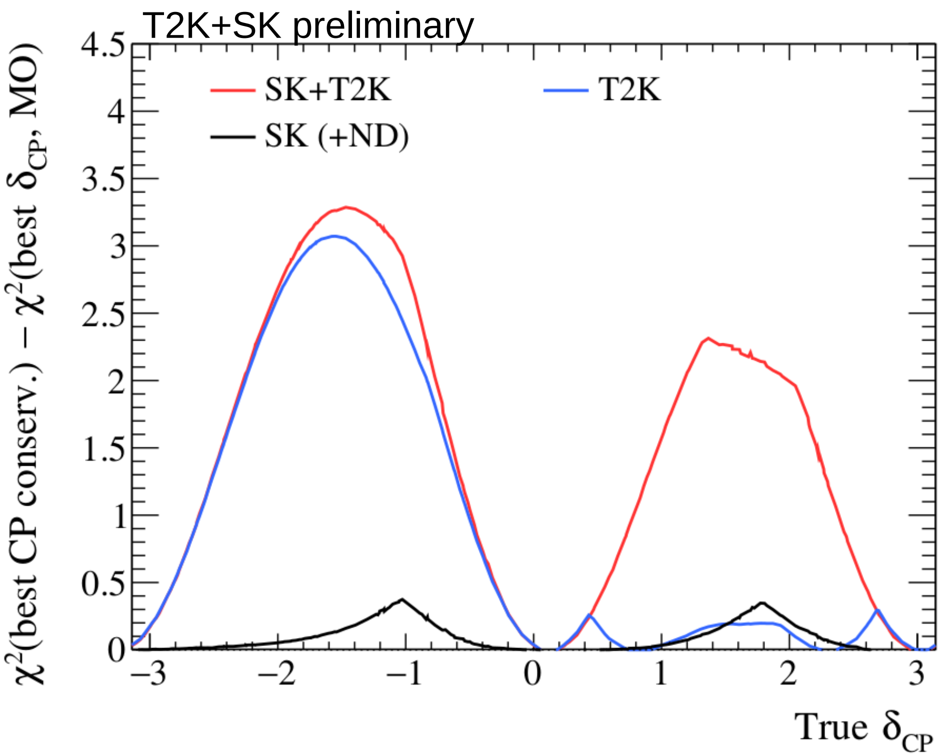
- Coherent MC for the 2 experiments
- Unified interaction model for T2K and low energy (sub-GeV) atmospheric samples
- High energy atmospheric neutrino use mainly interaction model from SK analysis
- Flux and detector models from each experiment, uncorrelated (tested effect of detector systematic correlations on sensitivities)



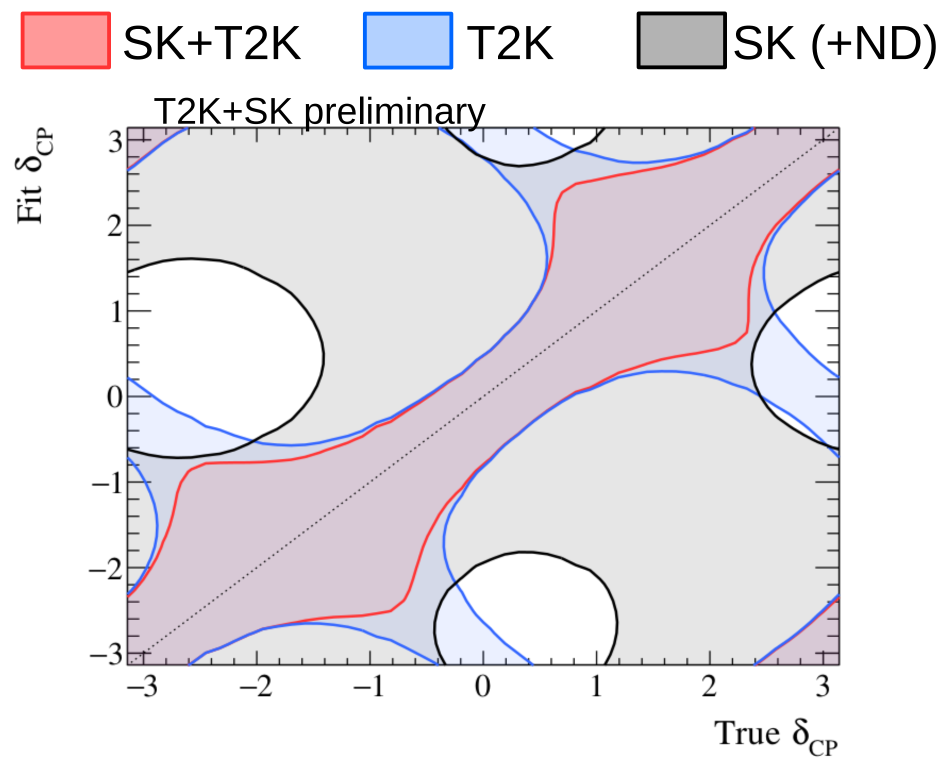
T2K-SK atmospheric joint analysis Sensitivity

- Sensitivity to δ_{CP} dominated by T2K
- Joint fit allows to break degeneracy with $\cos(\delta_{CP})$ and mass ordering

Ability to exclude CP conservation as a function of true δ_{CP} assumed



68% CL intervals for δ_{CP} as a function of true δ_{CP} assumed



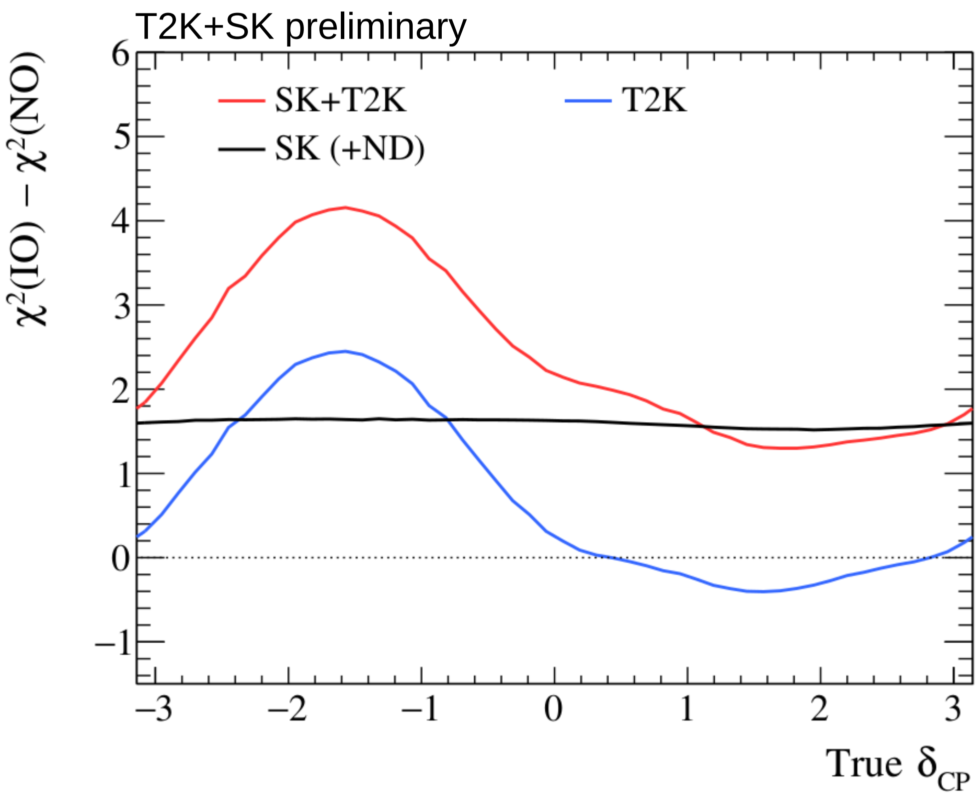
"SK (+ND)": T2K ND constraint on interaction uncertainties used for low E atmospheric samples

True values assumed: $\sin^2(\theta_{23})$=0.528, Δm^2_{32}=2.509x10^{-3} ev^2/c^4, $\sin^2(\theta_{13})$=0.0218, NO

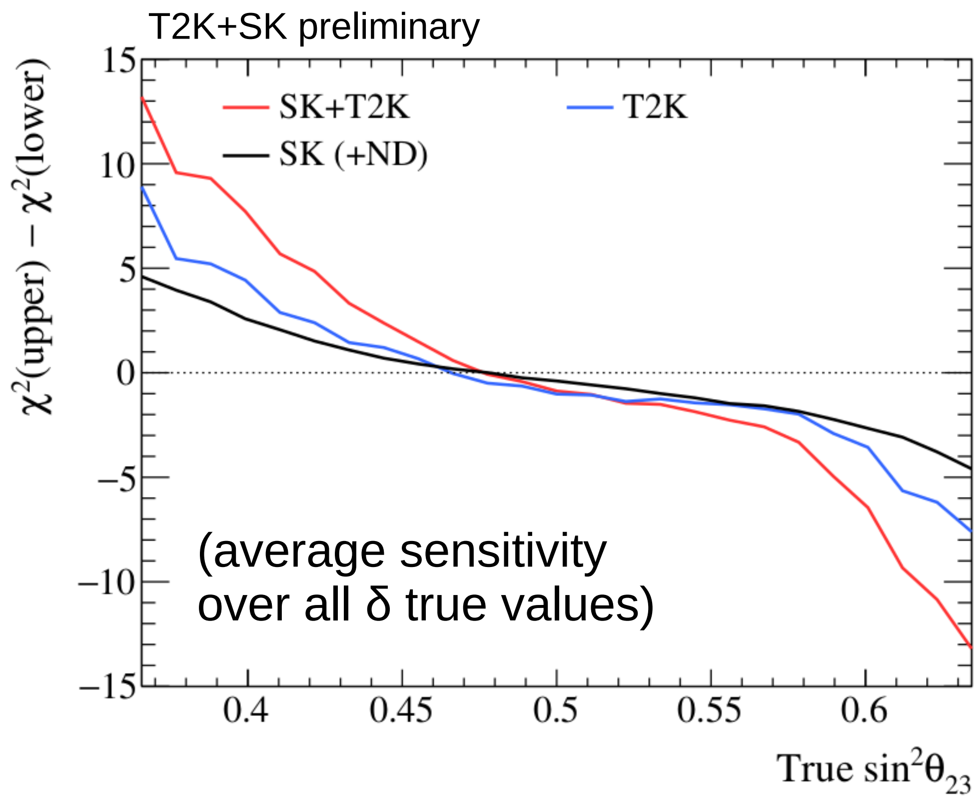
T2K-SK atmospheric joint analysis Sensitivity

- For mass ordering and θ_{23} octant, more similar contributions from the two experiments, with different dependence on true values of the parameters
- Joint fit gets an increased sensitivity compared to individual experiments as a result

Ability to reject wrong mass ordering



Ability to reject wrong θ_{23} octant



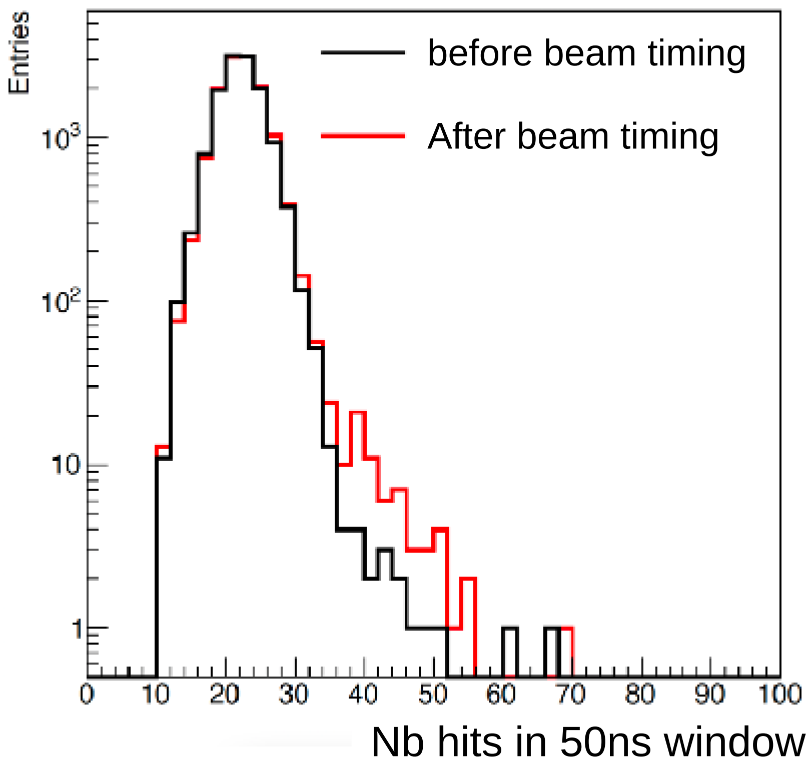
"SK (+ND)": T2K ND constraint on interaction uncertainties used for low E atmospheric samples

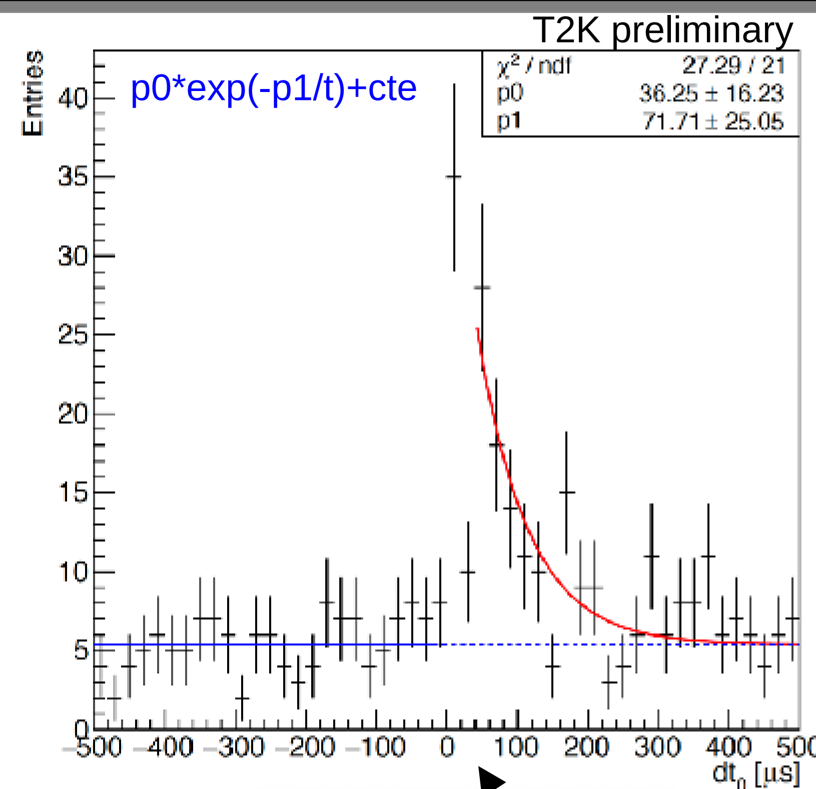
True values assumed: $\sin^2(\theta_{23})=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}$ eV^2/c^4, $\sin^2(\theta_{13})=0.0218$, NO

Neutron tagging using Gd

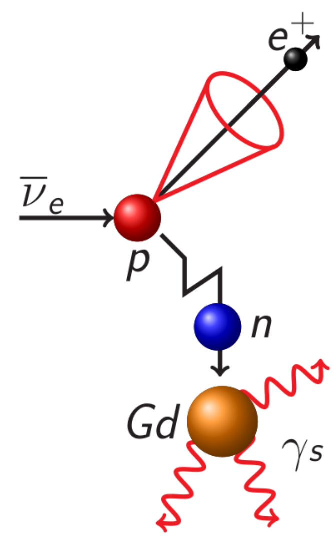
- During summer of 2020, Super-K was loaded with Gd sulfate, giving improved neutron tagging ability
- T2K already recorded data (“Run 11”) during this SK-Gd phase
- Not yet used in analysis, but could see the neutron capture signal in those data
- Potential for better neutron production measurements, and use of n tagging information in analysis

Events in 440µs window before and after expected beam timing





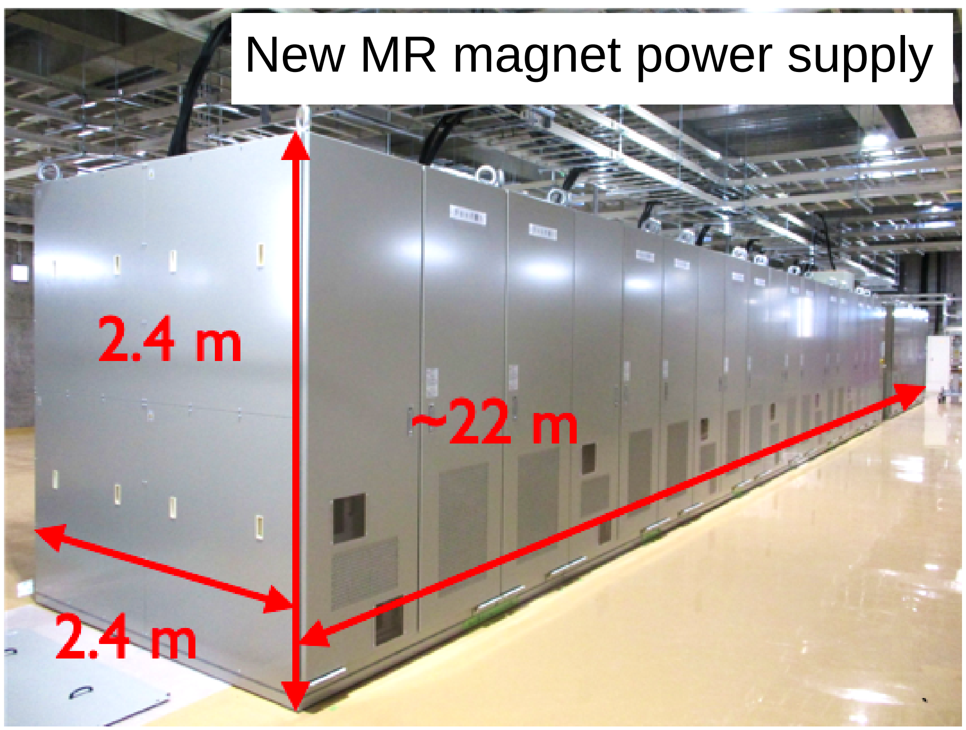
Exponential decrease of nb of events after beam timing. Time constant consistent with expected capture time on Gd (115 µs)



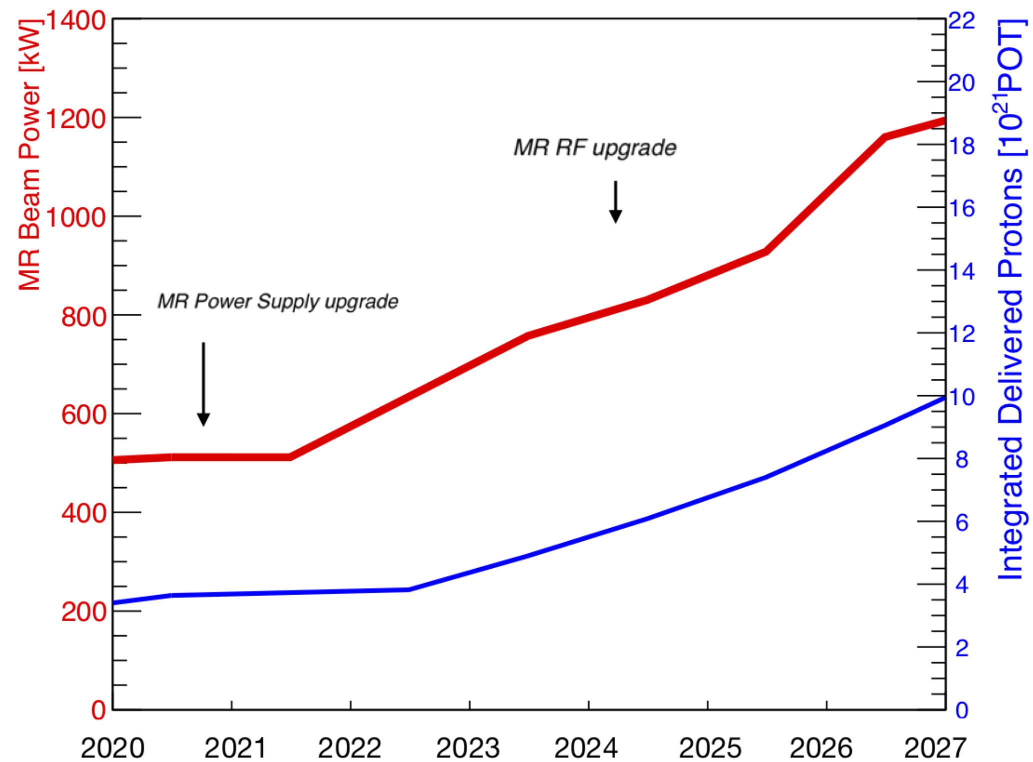
8 MeV γ cascade

J-PARC accelerator upgrade

- Proton beam reached ~515 kW stable operation in recent runs
- Long shutdown of the J-PARC main ring on-going, to upgrade magnet power supplies
- Will allow operation at higher intensity, via in particular reduced repetition rate
- Upgrade of the neutrino beamline in parallel to handle higher intensity beam
- Upgrade of horn power supplies will allow to operate them at higher current: 250→320 kA
- Expected to be ready for operation in early 2023

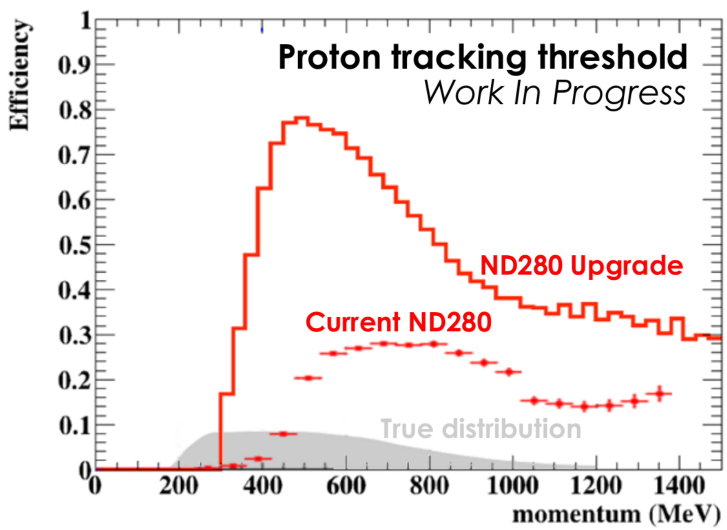


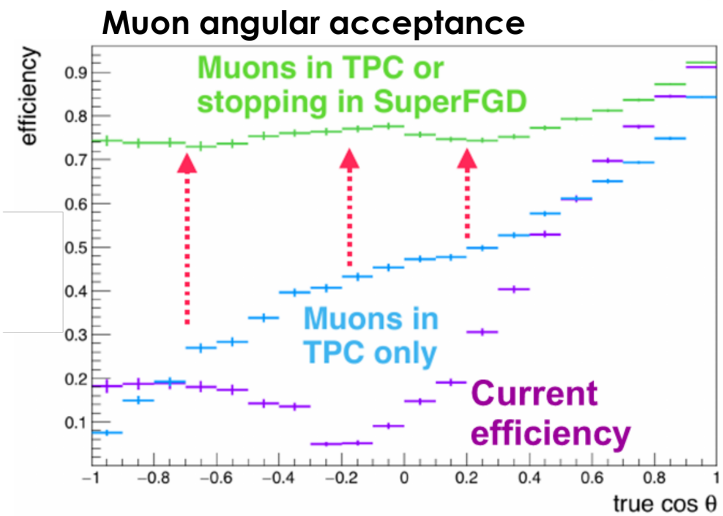
T2K Projected POT (Protons-On-Target)

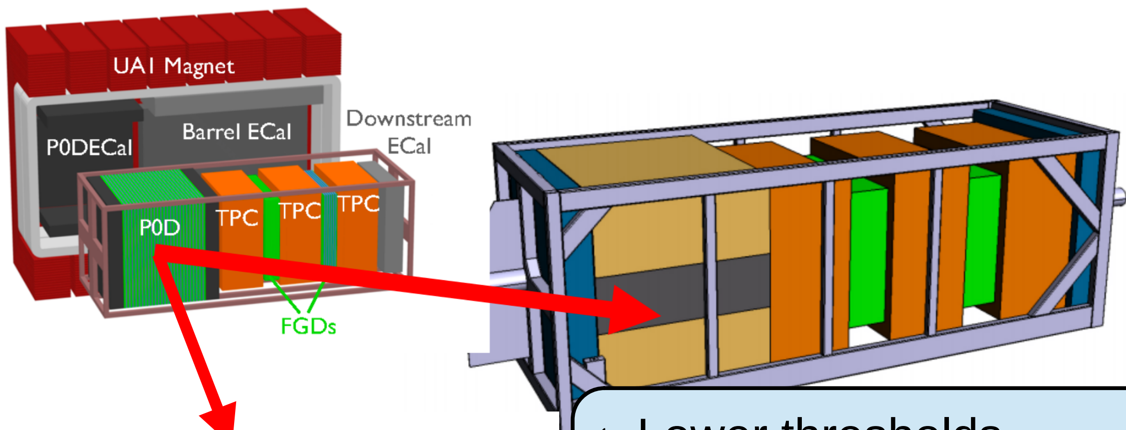


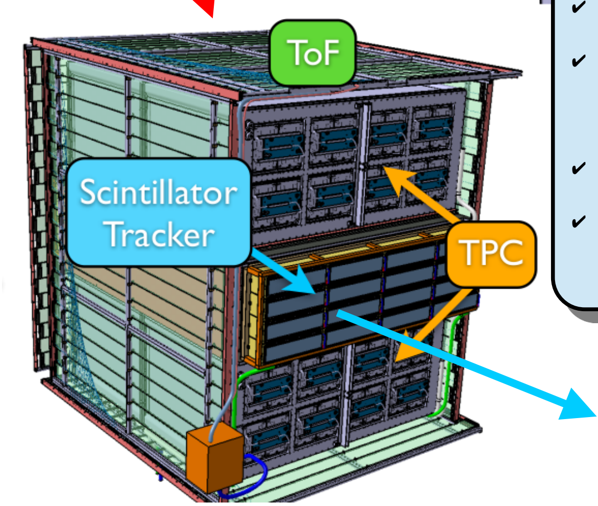
Near detector upgrade

- At the same time, upgrade of off-axis near detector
- Pi0 detector replaced by a complex of new detectors
- Improved ability to study neutrino interactions, both for cross-section measurements and constrain uncertainties in oscillation analysis
- Expect to start data taking in 2023

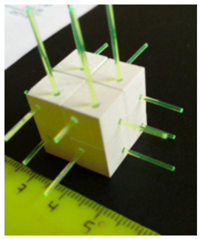








- ✓ Lower thresholds
- ✓ Improved efficiency for high angle tracks
- ✓ neutron reconstruction
- ✓ Improved determination of track directions



1 cm^3 cubes + WLS fibers

Summary

- T2K is a long baseline experiment studying neutrino oscillations, aiming for precise measurements of θ_{23}, Δm^2_{32} and looking for the neutrino mass ordering and possible CP violation in oscillations

- New analysis of the dataset presented at neutrino 2020 with significant improvements on all parts of the analysis:
  - Conservation of CP symmetry excluded at the 90% CL level
  - Mild preference for normal ordering and upper octant

- Data have been recorded during the SK-Gd phase, not yet added to the analysis

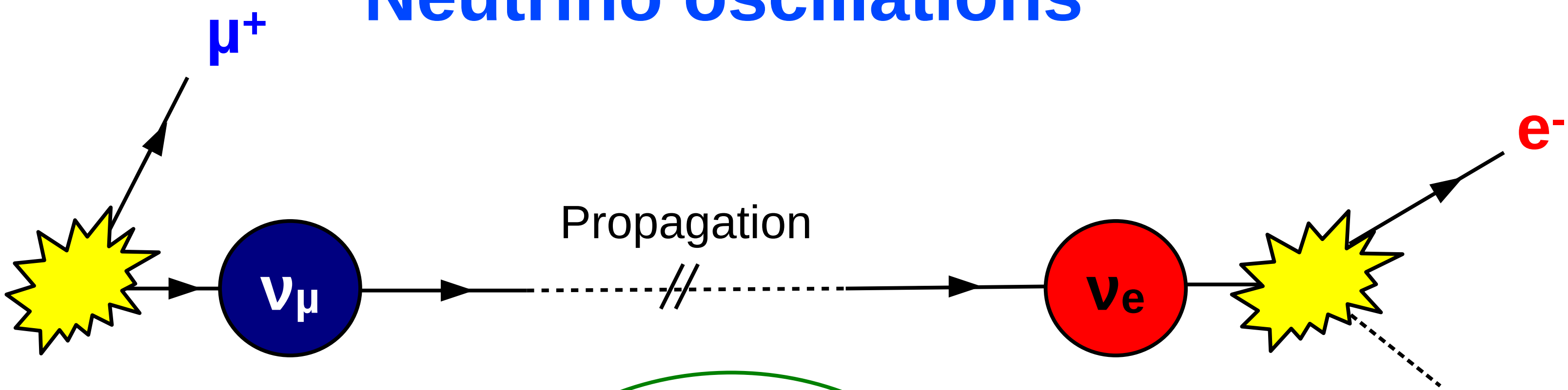
- Joint analyses with NOvA and Super-Kamiokande atmospheric in preparation

- On-going upgrade of the accelerator and near detectors, for operation at higher beam intensity and increased ability to study neutrino interactions

- In parallel, program of cross-section measurements to improve understanding of neutrino interactions

BACKUP

Neutrino oscillations



<u>Flavor eigenstates</u> (interaction)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

<u>Mass eigenstates</u> (propagation)

<u>Mixing (or Pontecorvo-Maki-Nagawa-Sakata) matrix</u>

link between the two sets of eigenstates

$P(\nu_\alpha \rightarrow \nu_\beta)$ oscillates as a function of distance L traveled by the neutrino with periodicity $\mathbf{\Delta m^2_{ij} L/E}$

($\Delta m^2_{ij} = m^2_i - m^2_j$)

Neutrino oscillations
Parameters

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

$P(\nu_\alpha \rightarrow \nu_\beta)$ depends on 6 parameters:

- 3 **mixing angles** : $\theta_{12}, \theta_{23}, \theta_{13}$
- 2 **mass splittings** : Δm^2_{ij}
- 1 (complex) phase : The **CP phase δ**

Amplitude

Periodicity

Difference in oscillations $\nu/\bar{\nu}$

$$P(\nu_\alpha \rightarrow \nu_\beta, U) = P(\overline{\nu_\alpha} \rightarrow \overline{\nu_\beta}, U^*)$$

Sensitivity to open questions

δ and the mass ordering modify the electron to muon flavor oscillation probability in different ways for neutrinos and anti-neutrinos

Full probability in vacuum:

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$
$$+ 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$- 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$+ 4s_{12}^2 c_{13}^2(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$

$\sin^2\Delta_{ij} = \sin^2(1.27\,\Delta m_{ij}^2 \times L/E),\ s_{ij} = \sin(\theta_{ij}),\ c_{ij} = \cos(\theta_{ij})$

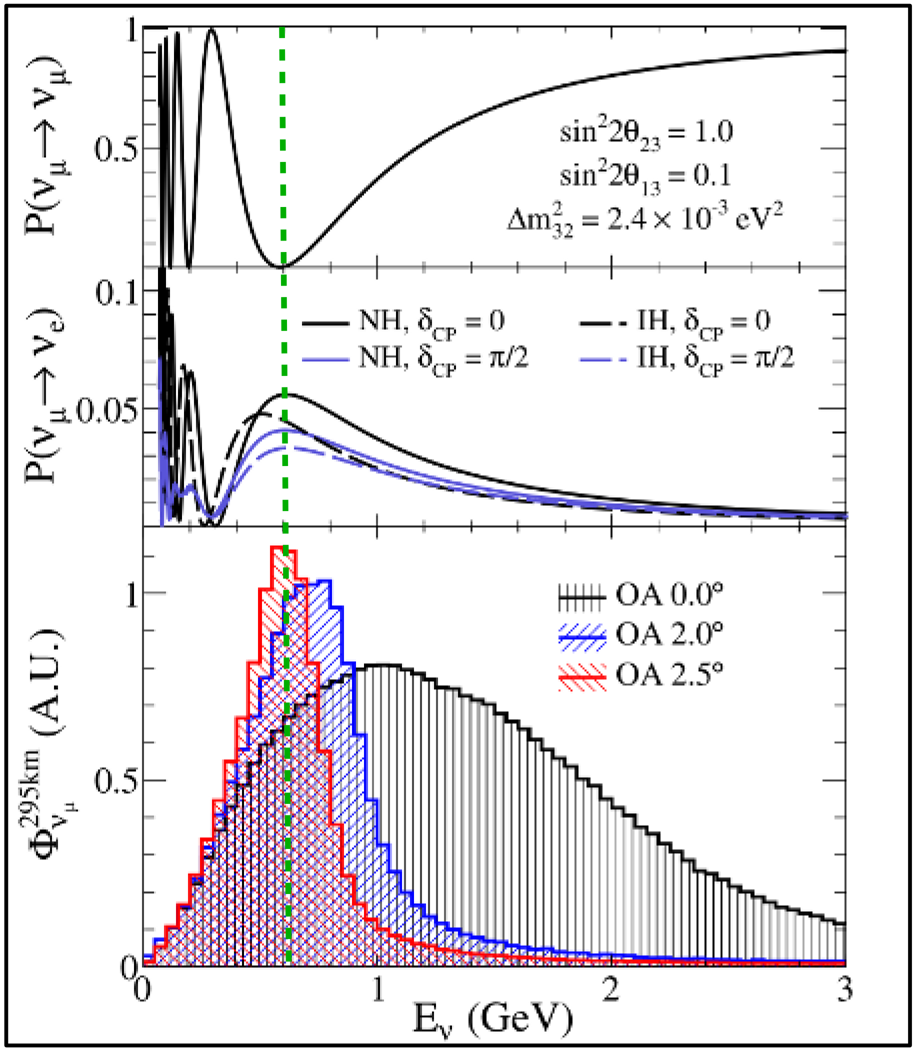
$\nu \to \bar{\nu}$
$\delta \to -\delta$
$x \to -x$

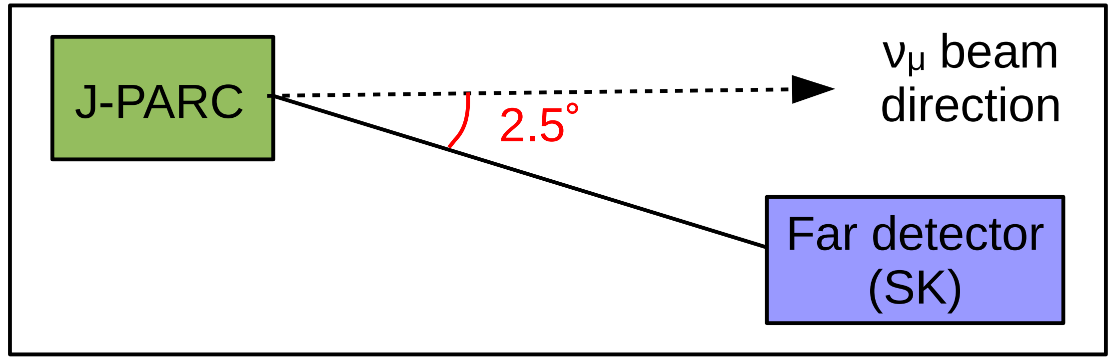
In matter leading term

$$P(\nu_\mu \to \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2}{E}\right)$$

Multiplied by $$\frac{\sin^2(\Delta(1-x))}{(1-x)^2}$$

The T2K experiment
Off-axis beam



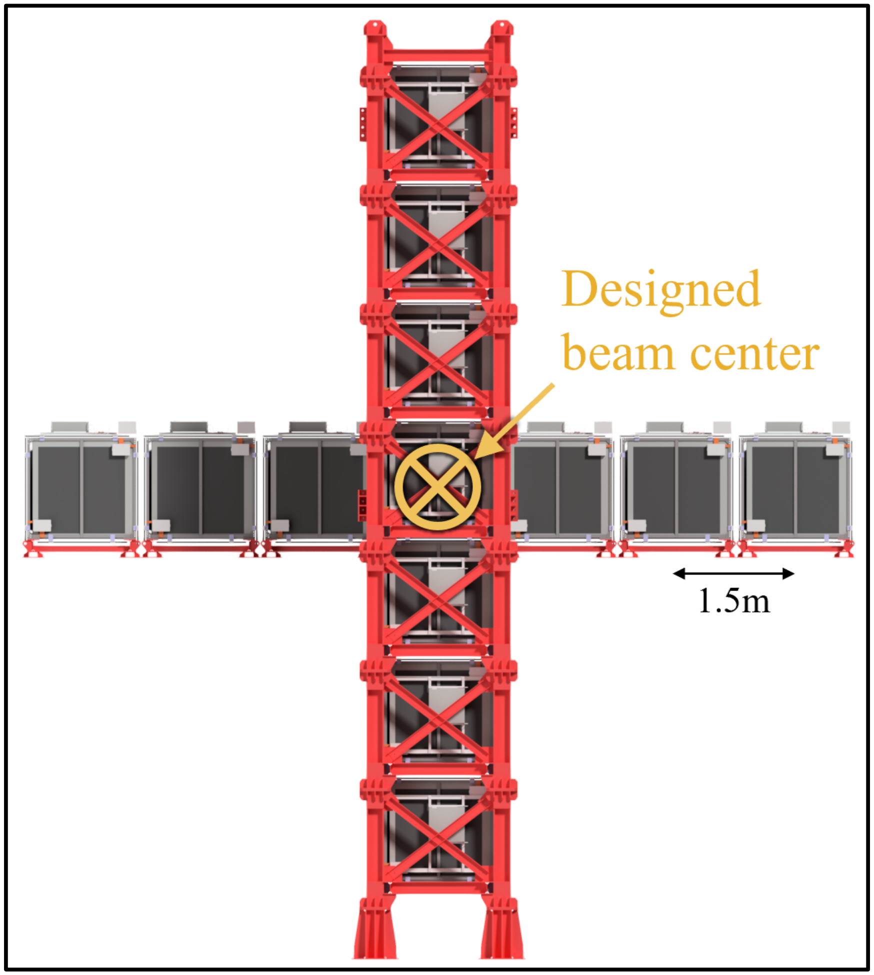


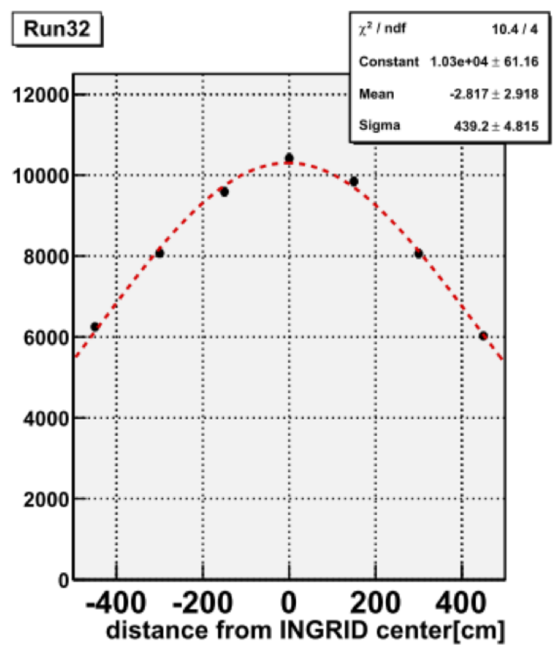
- Narrow band neutrino beam, peaked at oscillation maximum (0.6 GeV)
- Reduces high energy tail
- Reduces intrinsic ν_e contamination of the beam at peak energy
- Interactions dominated by CCQE mode

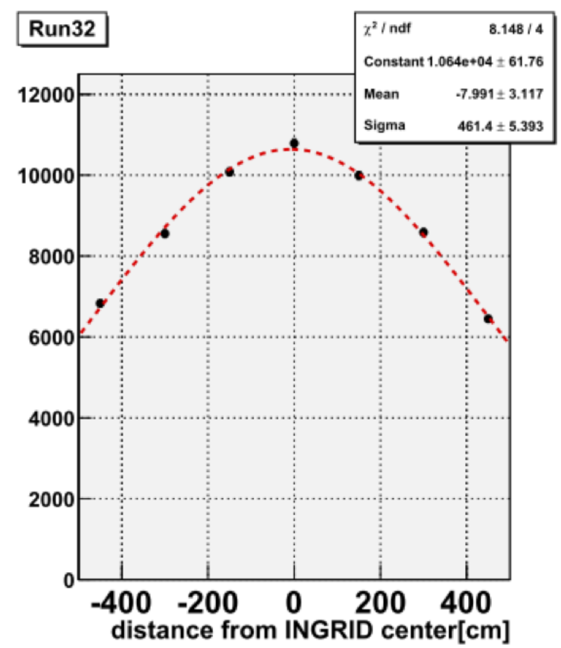
The T2K experiment
Near detectors

On-axis detector INGRID (Interactive Neutrino GRID)
Located 280m from the target

- 14 identical modules made of iron and scintillators
- 'counting neutrinos' by reconstructing muon tracks from ν_μ interactions
- Monitors neutrino beam: rate, direction and stability

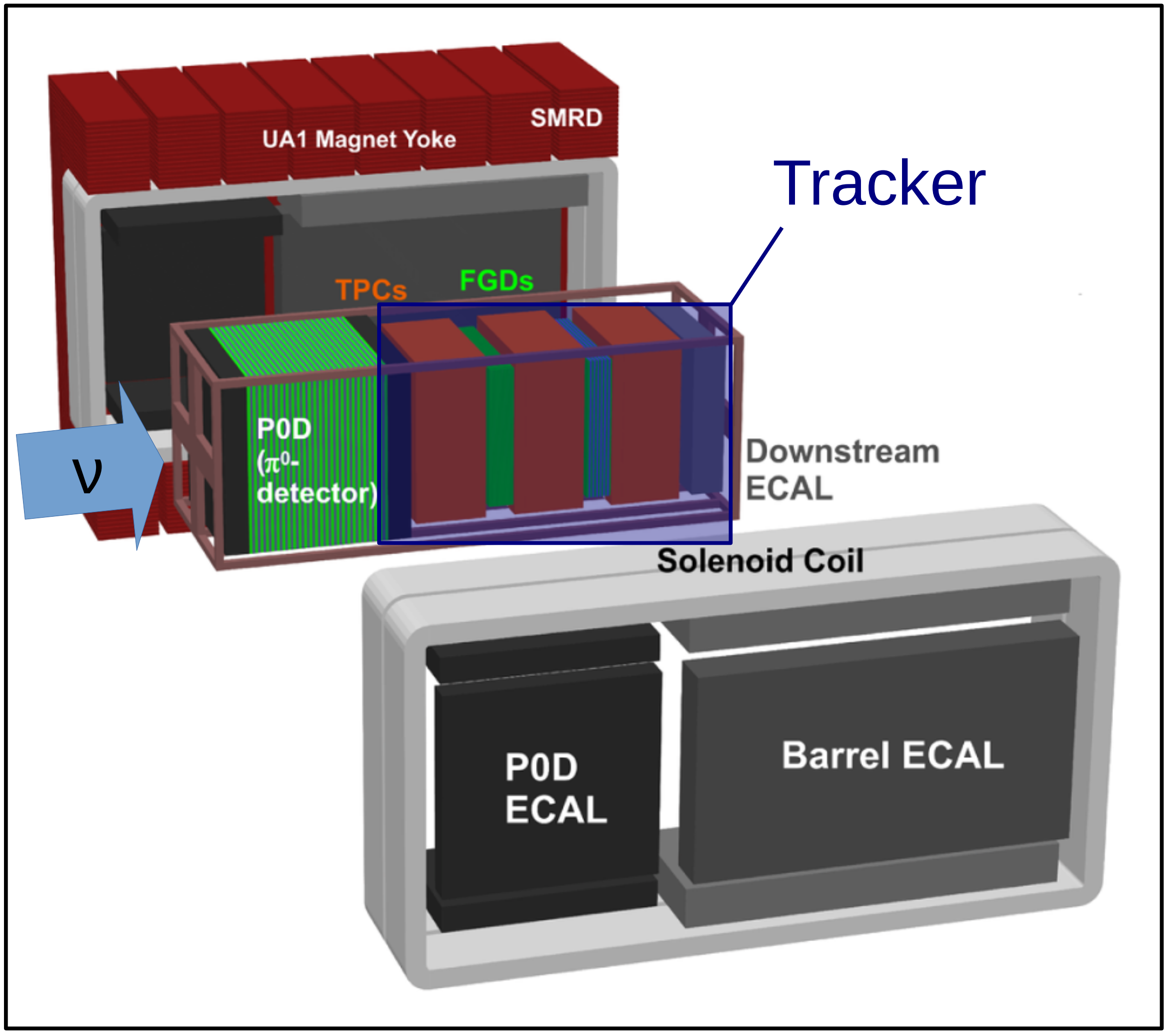




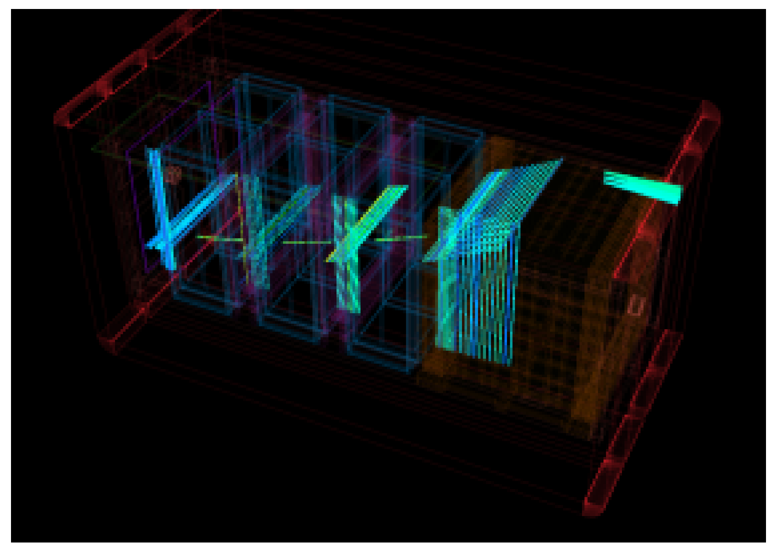


The T2K experiment
Off-axis near detectors

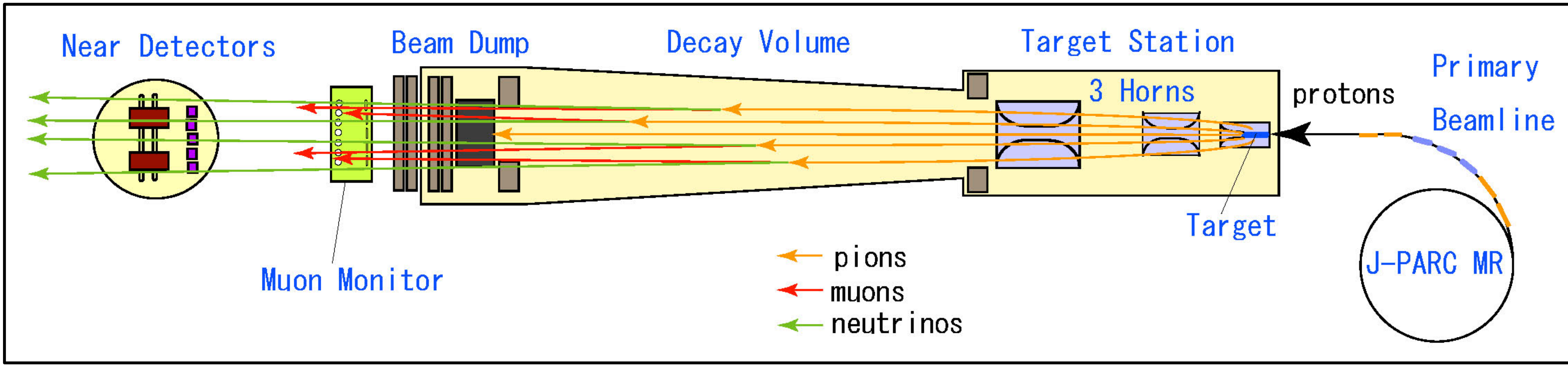
Off-axis near detector ND280
Located 280m from the target



- Several detectors inside a 0.2 T magnetic field
- Good tracking capabilities
- 'Tracker' used to constrain flux and interaction uncertainties for oscillation analysis
- Rich cross-section measurement program

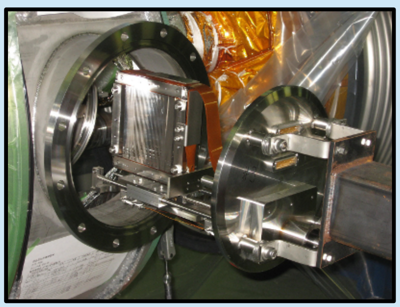


Neutrino flux prediction



Neutrino flux predicted using a series of simulations

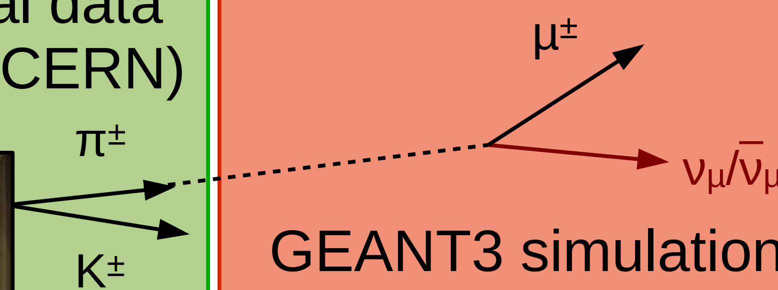
Proton beam properties



Measured by beam monitors

Hadron production in target

FLUKA
Tuned to external data
(NA61/SHINE@CERN)

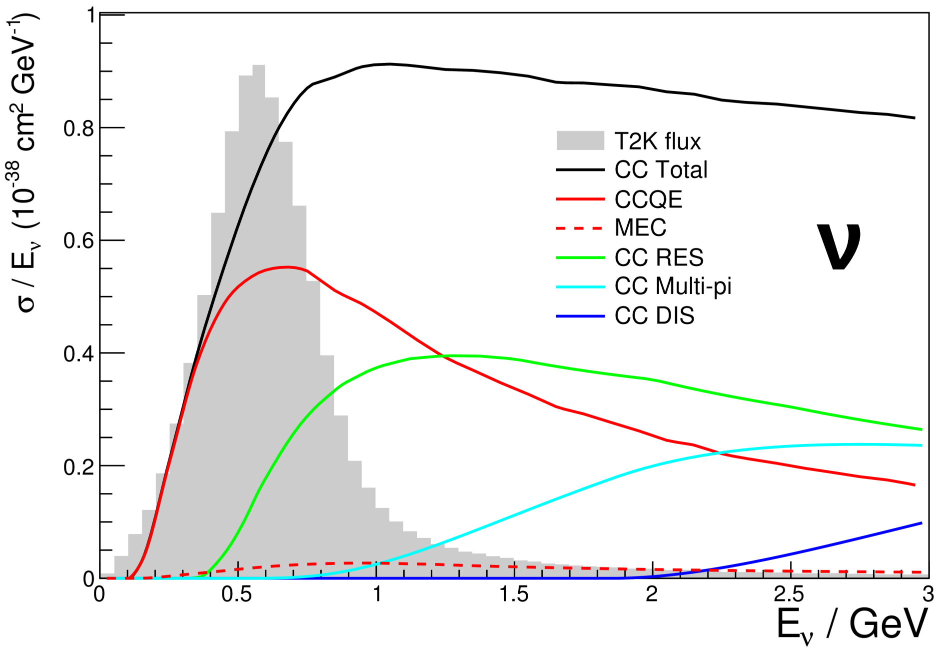


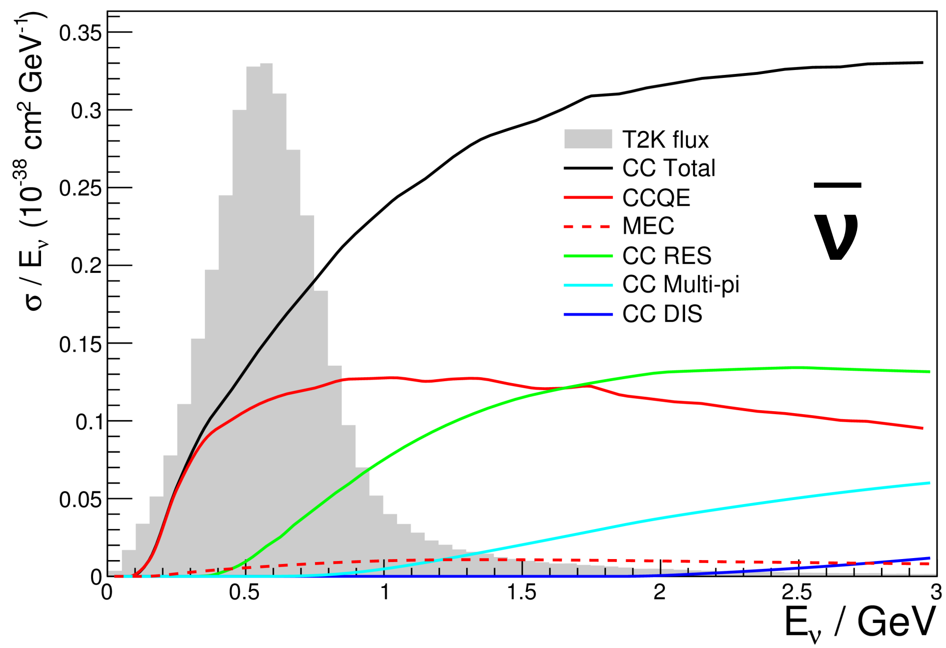
Propagation and decay of hadrons in secondary beamline

GEANT3 simulation
GCALOR package
(tuned to external data)

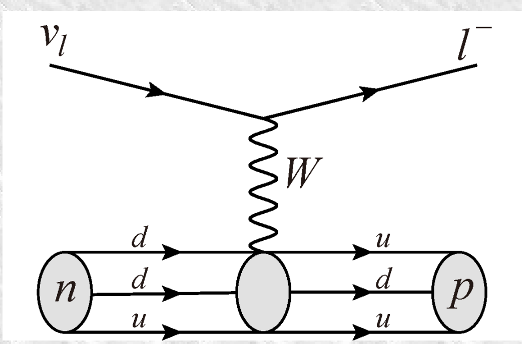
Neutrino interactions

- Need to detect neutrino flavor => charged-current interactions
- At T2K energies, dominant interaction mode is charged-current quasi-elastic

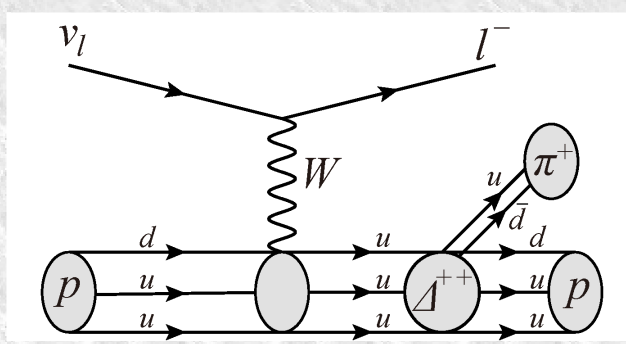




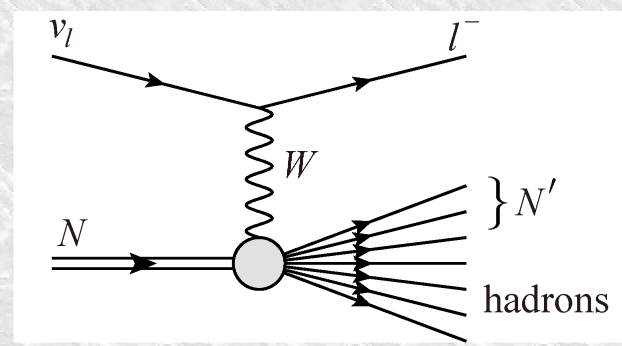
CCQE



CC RES



CC DIS/Multi-pi

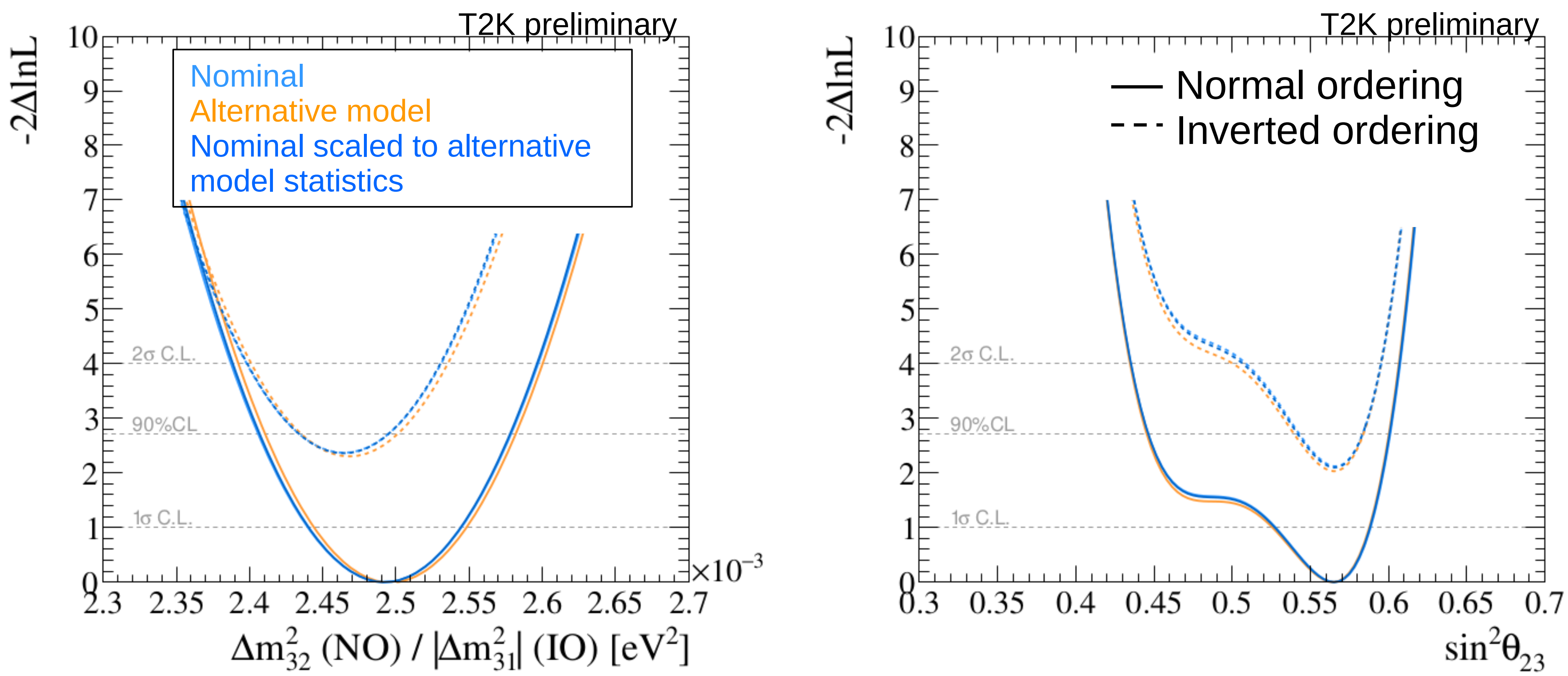


Test of alternative interaction models
Simulated data studies

Look for possible biases by comparing sensitivities obtained when fitting our model to data generated with nominal and modified interaction models:

- Data driven (assign ND data/MC difference to 1 mode)
- Alternative models (form factors, 2p2h, nuclear model, ...)

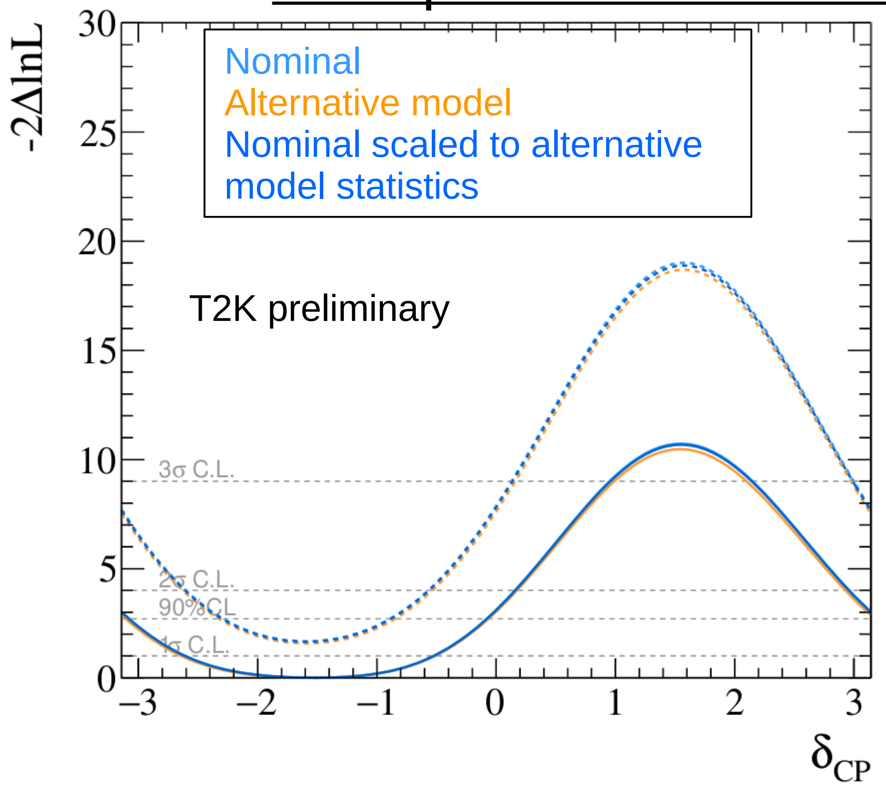
Example: Pion kinematics alteration for resonant events

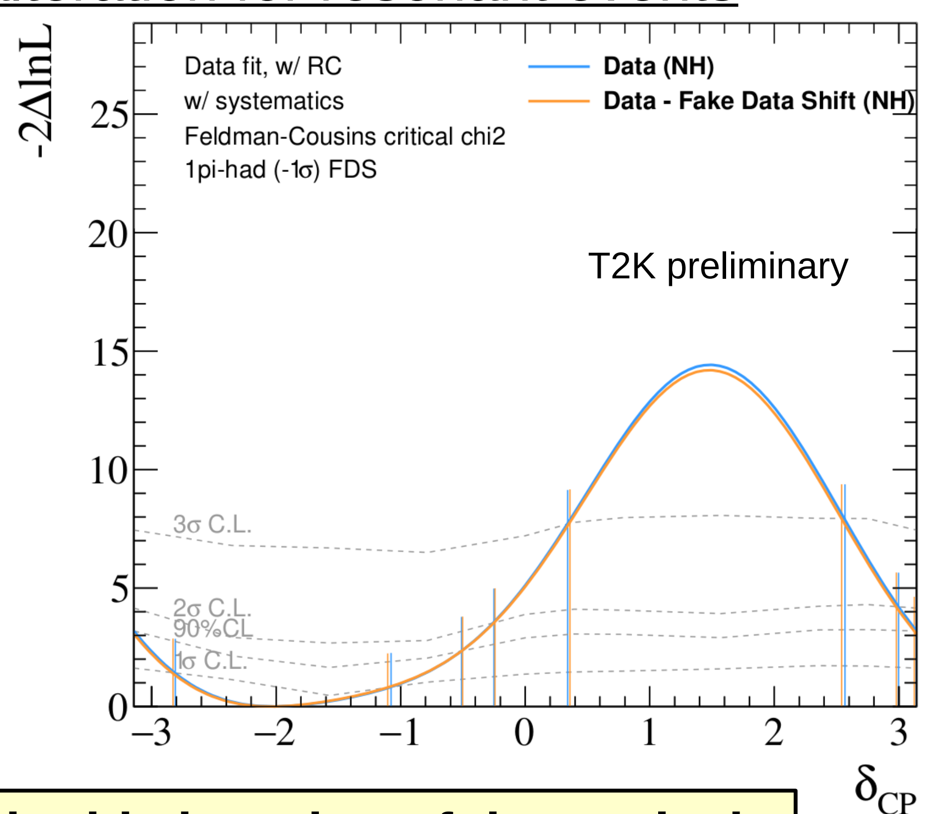


Test of alternative interaction models
Simulated data studies

- If significant differences are found:
  - further investigation
  - for Δm^2, apply Gaussian smearing corresponding to bias observed
  - Can add additional empirical systematic parameters from difference seen (only used once in a previous analysis)
- For δ, check if change of $\Delta\chi^2$ corresponding to difference with alternative model would change the main conclusion of data fit (eg CP conservation excluded at 90% CL)

Example: Pion kinematics alteration for resonant events





No significant biases found for δ and θ_{23} in this iteration of the analysis

Systematic uncertainties
Oscillation analysis, far detector fit

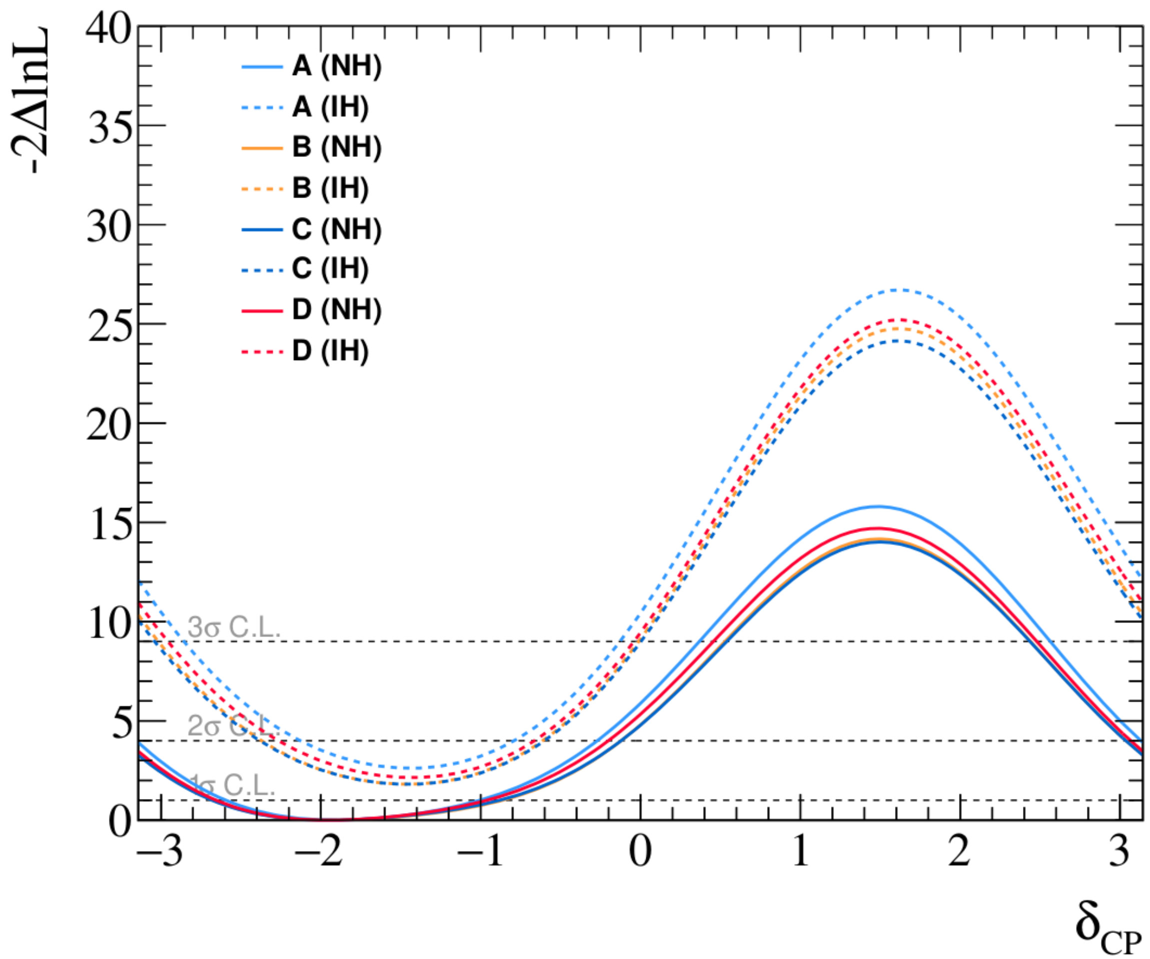
Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6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

Note:

- Numbers quoted are the RMS of the predicted numbers of events in the far detector sample obtained when varying systematic parameters according to their prior distribution
- Some systematic parameters do not have a prior constraint, and can end up having larger effect than estimated with this method in a fit

New oscillation results
Effect of analysis change - δ_{CP}

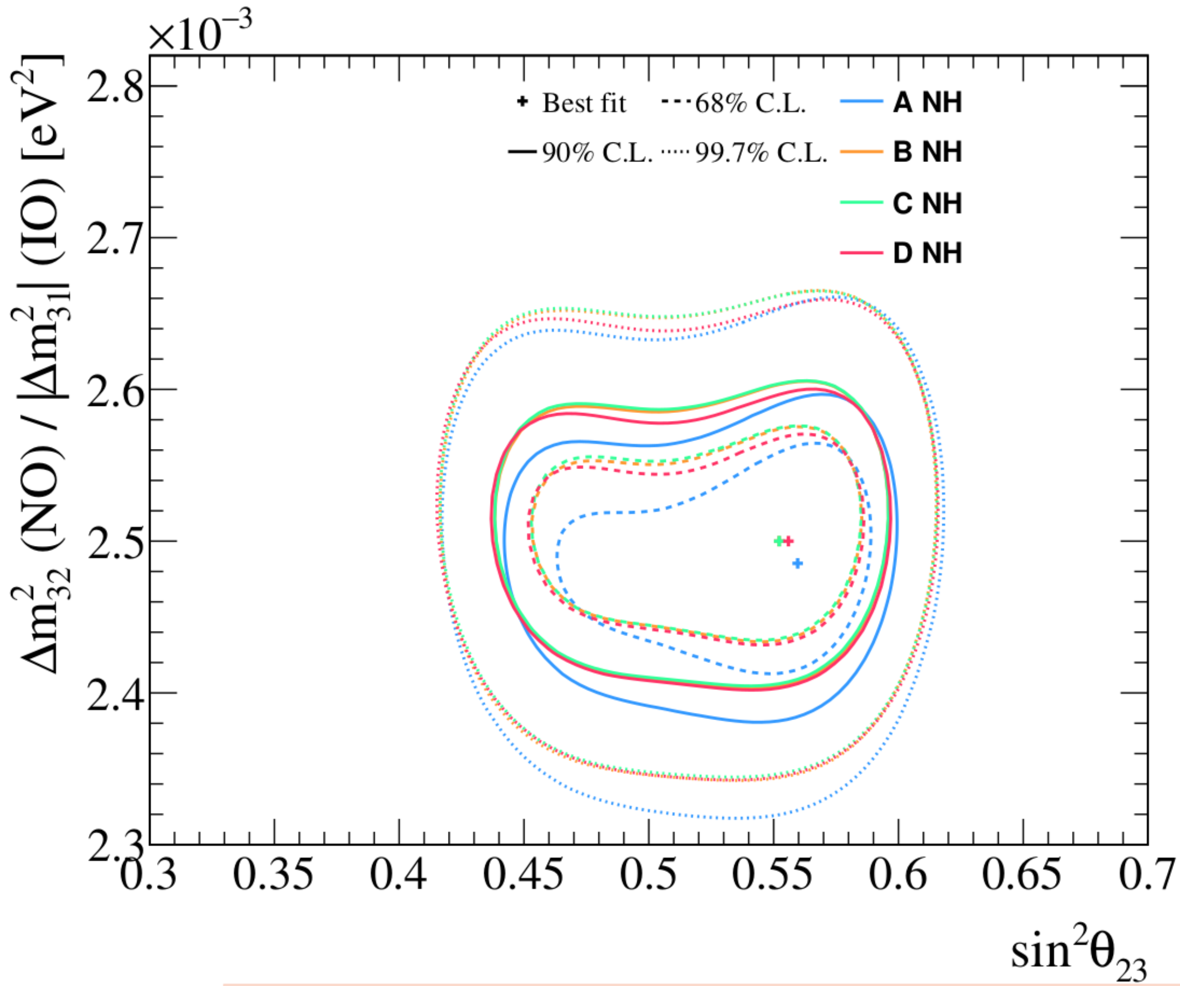
A: Neutrino 2020 result
B: New interaction model and near detector fit
C: B + new θ_{13} reactor constraint (PDG 2019 → PDG2021)
D: C + new sample (ν_μ CC1π^+)



Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

New oscillation results
Effect of analysis change - Atmospheric

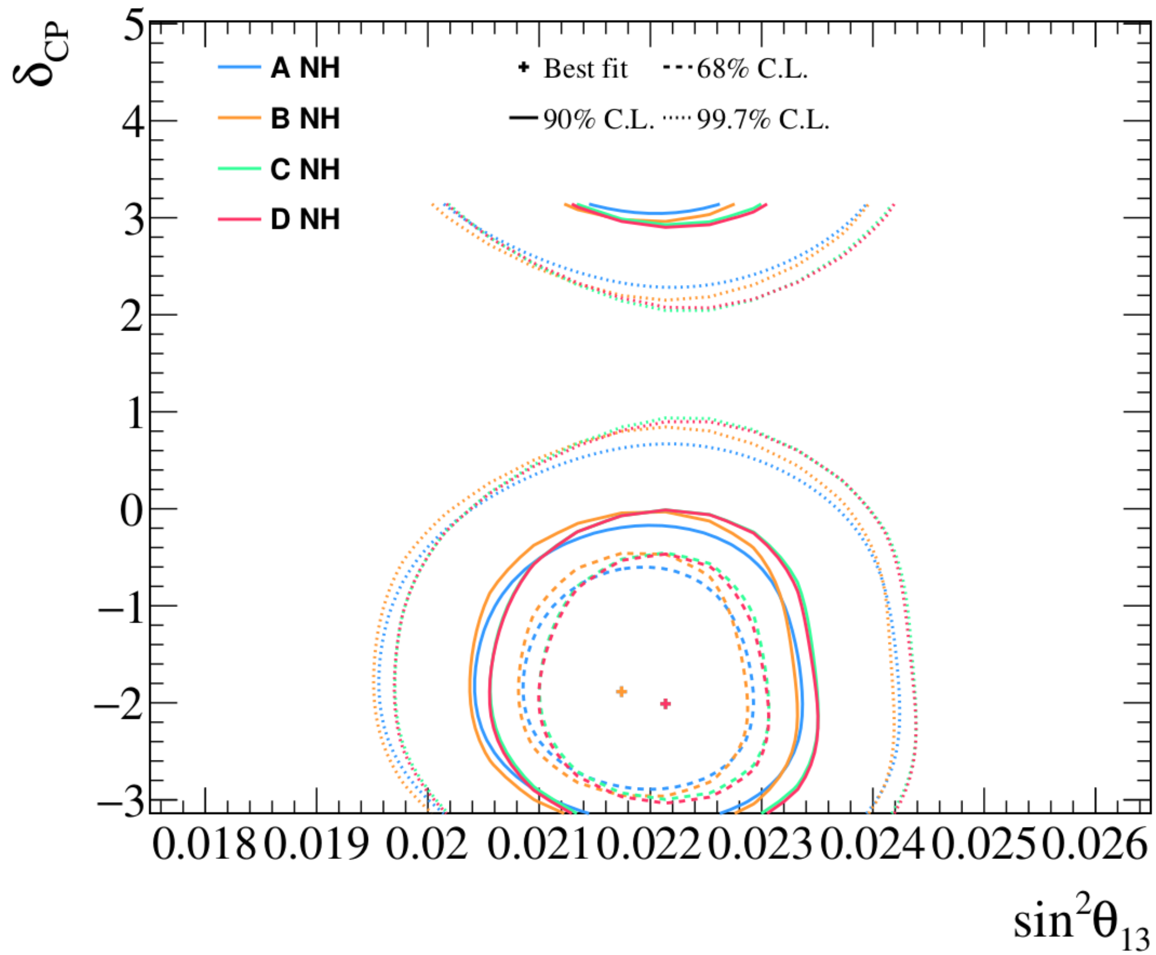
A: Neutrino 2020 result
B: New interaction model and near detector fit
C: B + new θ_{13} reactor constraint (PDG 2019 → PDG2021)
D: C + new sample (ν_μ CC1π^+)



Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

New oscillation results
Effect of analysis change - Appearance

A: Neutrino 2020 result
B: New interaction model and near detector fit
C: B + new θ_{13} reactor constraint (PDG 2019 → PDG2021)
D: C + new sample (ν_μ CC1π^+)



Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

ν_μ and $\bar{\nu}_\mu$ CCCoherent Cross Section

- New measurement of CC coherent pion production cross-section on carbon
- For ν_μ, increased statistics and reduced systematics compared to previous T2K result (PRL 117, 192501 (2016))
- For $\bar{\nu}_\mu$, first measurement on carbon at sub-GeV energies

Assuming cross section scales with atomic mass number as $A^{1/3}$:

$$\nu_\mu \ \sigma^{\text{CC-COH}}_{^{12}\text{C}} = 2.98 \pm 0.37(\text{stat.}) \pm 0.58(\text{syst.}) \times 10^{-40}\text{cm}^2$$

$$\bar{\nu}_\mu \ \sigma^{\text{CC-COH}}_{^{12}\text{C}} = 3.05 \pm 0.71(\text{stat.}) \pm 0.84(\text{syst.}) \times 10^{-40}\text{cm}^2$$

(flux integrated)

T2K preliminary

CC – coherent $\pi^\pm$