Status and Plans of T2K

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Interplay between Particle and Astroparticle physics

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NCBJ

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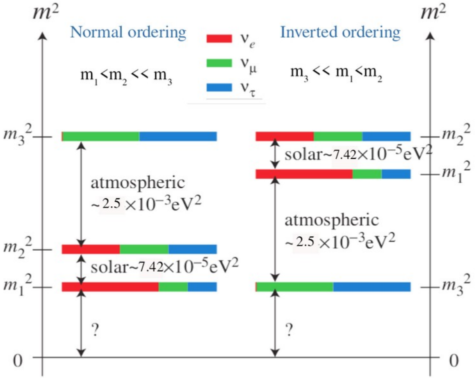
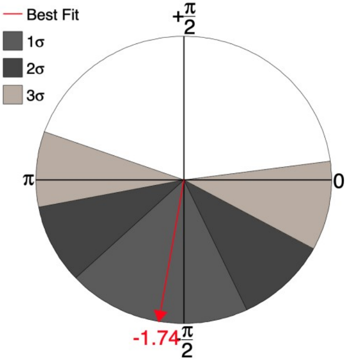
Current Open Questions in Neutrino Oscillations

- Neutrino mass ordering



- Leptonic CP phase

Nature 580, 339–344 (2020)



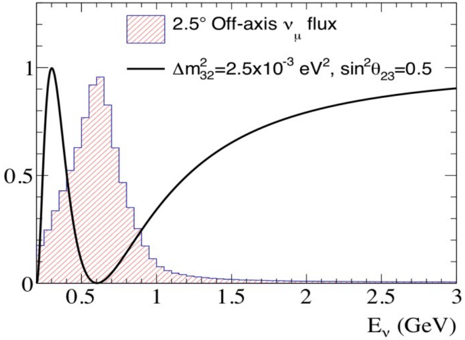
- Octant of the mixing angle θ_{23}

$\theta_{23} < (>)\ 45^o$ Lower (upper) octant

$\theta_{23} = 45^o$ Maximal mixing

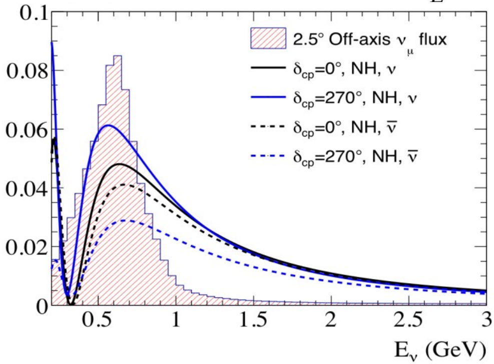
Neutrino oscillation probabilities at T2K

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



- Sensitivity to $\sin^2(2\theta_{23})$, $|\Delta m^2_{32}|$

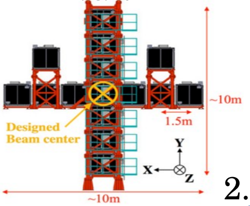
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$$



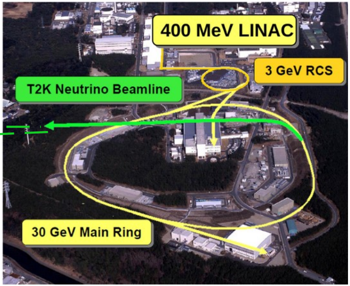
- Sensitivity to $\sin^2(2\theta_{13})$, $\sin^2\theta_{23}$ (θ_{23} octant)
- Sensitive to CP phase δ_{CP}
- L = 295 km “not very long” → δ_{CP} effect dominates compared to that of mass ordering(~<27% vs ~10%)

Tokai-2-Kamioka

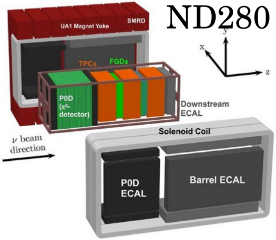
INGRID

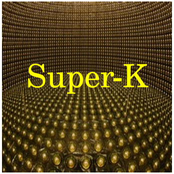


2.5°



ND280





295 km

280 m

0 m

Far Detector
Super-Kamiokande

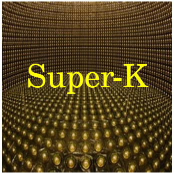
$N_{FD} \sim \Phi_{FD} \cdot \sigma_{FD} \cdot \varepsilon_{FD} \cdot P_{osc}$

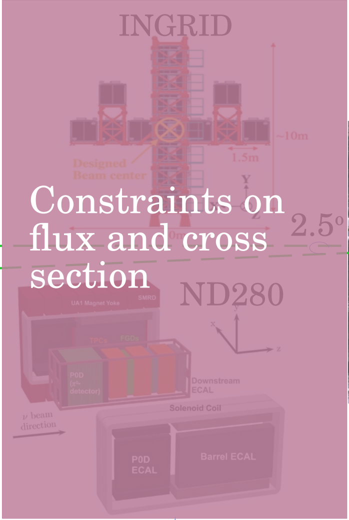
Near Detectors
On Axis – INGRID
2.5° Off Axis – ND280

$N_{ND} \sim \Phi_{ND} \cdot \sigma_{ND} \cdot \varepsilon_{ND}$

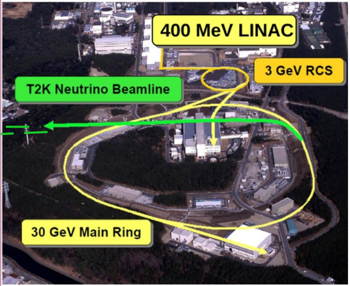
J-PARC
Accelerator complex
Neutrino beamline

Tokai-2-Kamioka





Constraints on flux and cross section



295 km | 280 m | 0 m

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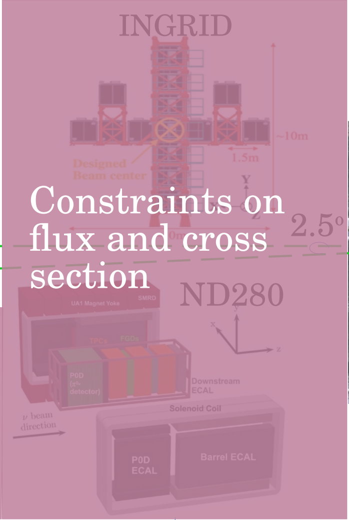
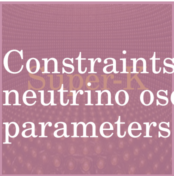
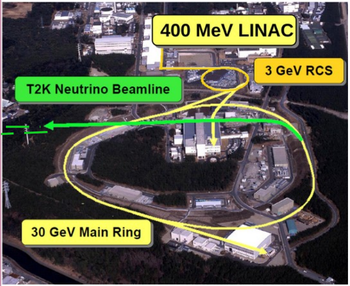


Constraints on flux and cross section



Constraints on neutrino oscillation parameters



295 km

280 m

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Far Detector
Super-Kamiokande

$N_{FD} \sim \Phi_{FD} \cdot \sigma_{FD} \cdot \varepsilon_{FD} \cdot P_{osc}$

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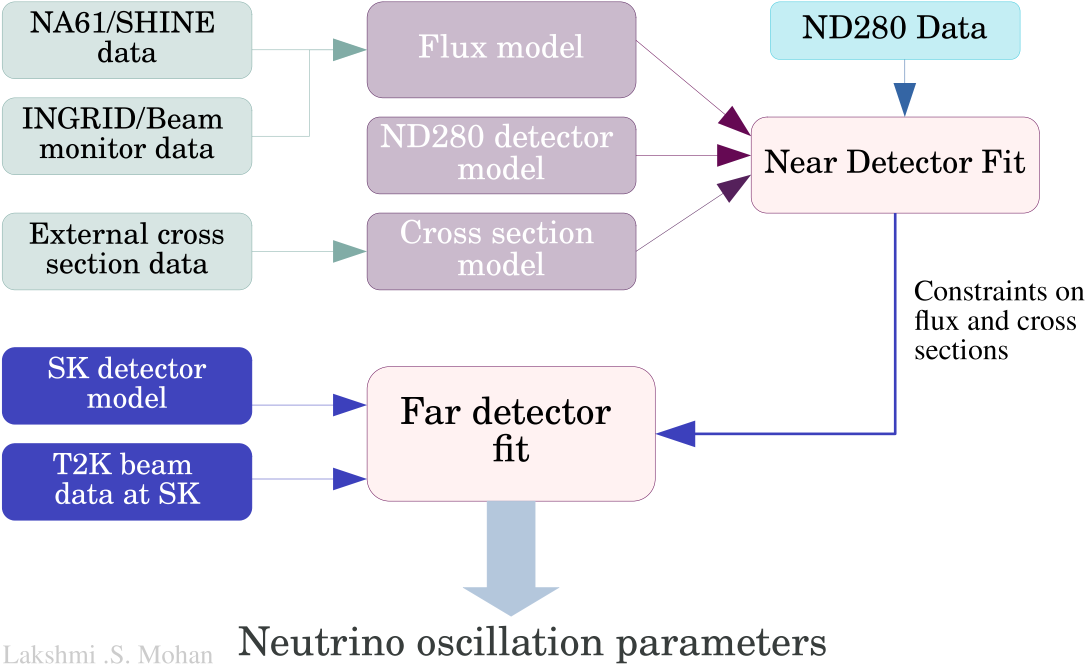
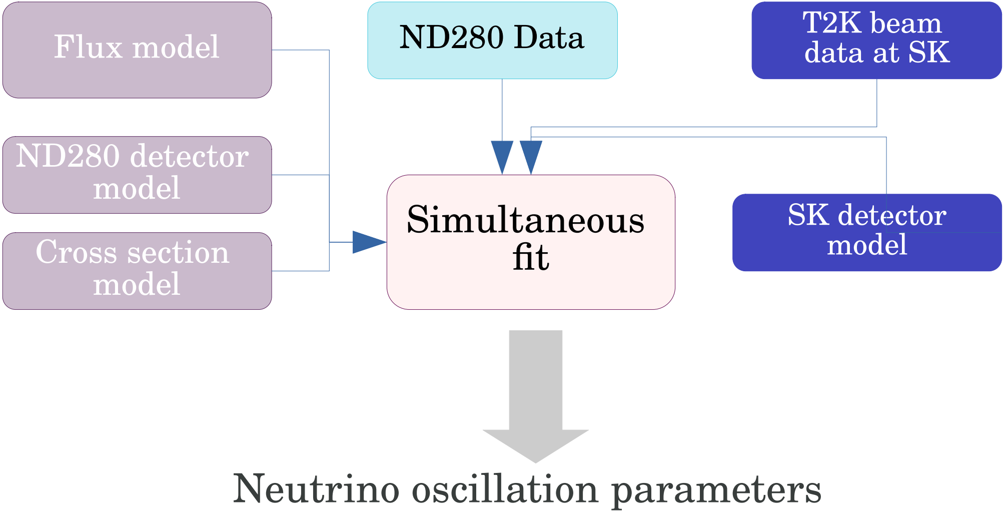
$N_{ND} \sim \Phi_{ND} \cdot \sigma_{ND} \cdot \varepsilon_{ND}$

J-PARC
Accelerator complex
Neutrino beamline

T2K analysis 1: Consecutive ND+FD fit and Frequentist Approach

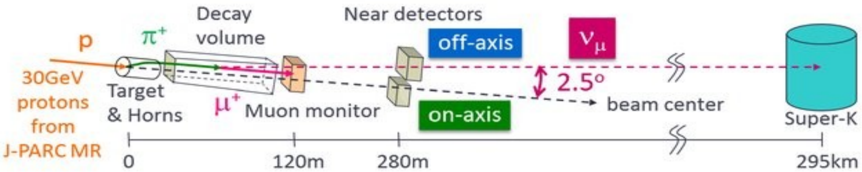


T2K analysis 2: Simultaneous ND+FD fit and Bayesian Approach



Inputs to the fit

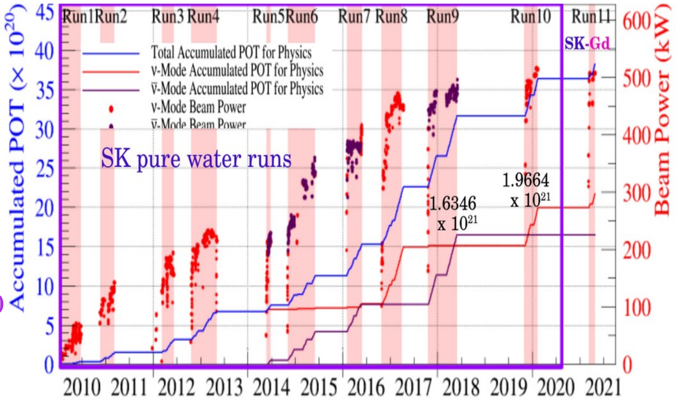
T2K beam



(FHC) $\pi^+ \rightarrow \mu^+ + \nu_\mu$

(RHC) $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

- Total POT accumulated from Jan 2010 - April 2021: 3.82 x 10^{21}
- Maximum beam power 522.6 kW



This talk

Used for this analysis – Run 1-10
Total POT : 3.6 x 10^{21}

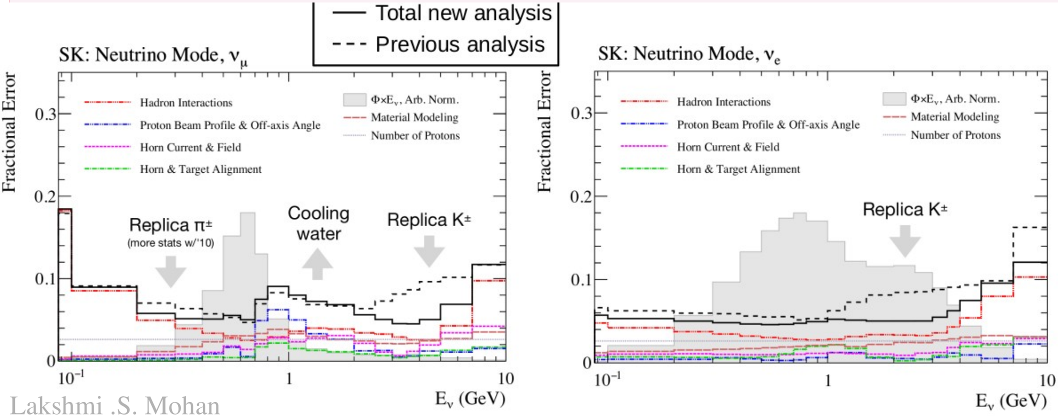
ν-mode: 1.9664 x 10^{21} (54.6%)

$\bar{\nu}$-mode: 1.6346 x 10^{21} (45.4%)

Flux predictions and uncertainties

- Simulation with FLUKA/GEANT3/GCALOR.
- Flux tuning based on NA61/SHINE hadron production measurements using 2010 T2K replica target data, EPJ C 79, 100 (2019).

  ➔ Has more statistics for $\pi^{\pm}$ production
  ➔ Added $K^{\pm}$ and proton data



Updated neutrino interaction model

1) CCQE model based on Spectral Function

   a) New uncertainties on nuclear shell structure, nuclear potential and Pauli Blocking

   b) Nucleon removal energy has a parameterized dependence on momentum transfer

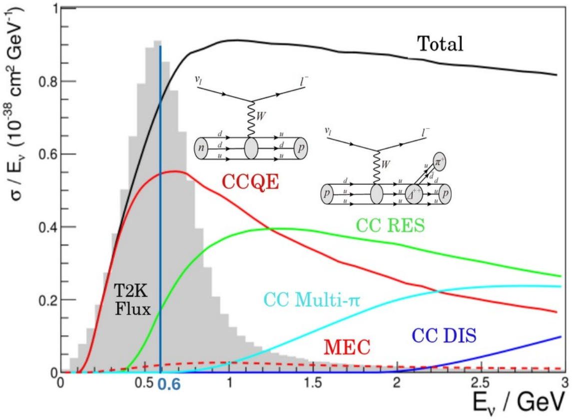
2) CC RES: Based on Rein–Sehgal (RS) model with RFG nuclear model

   a) New bubble chamber tune of RS parameters

   b) New resonance decay uncertainties

   c) Effective inclusion of binding energy

   d) New uncertainty in $\pi^{\pm}$ vs π^{0} production

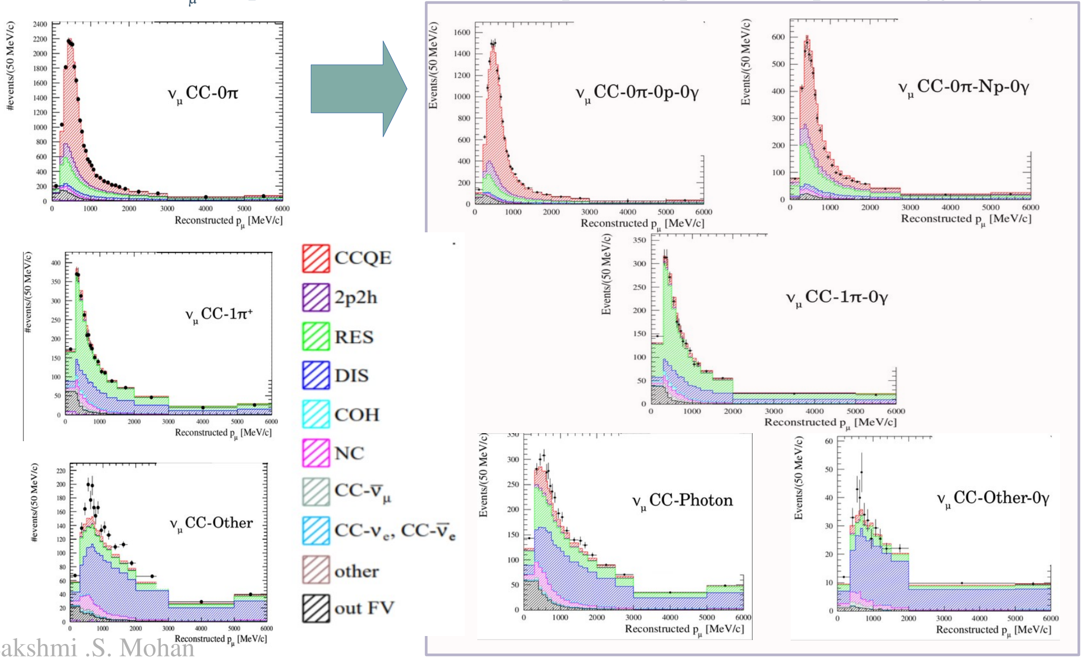


3) Better description of 2p2h (MEC) contribution from pn/nn pairs

4) Improvements to multi-pion production and final state interaction model

ND280 samples for this analysis → 22 samples

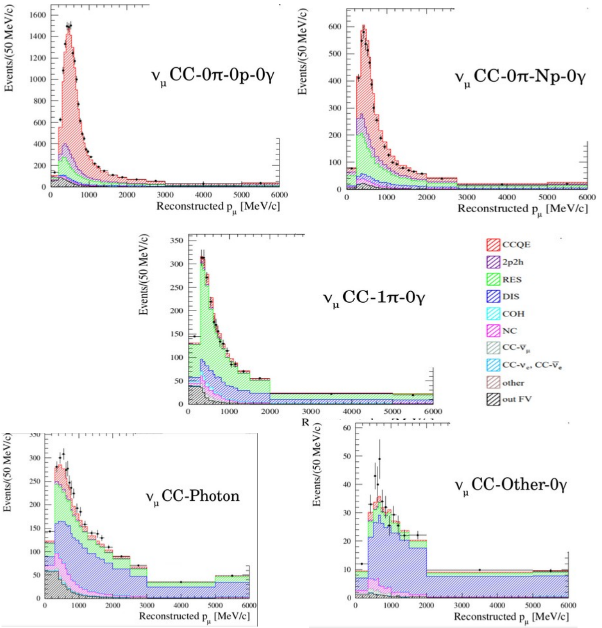
- New FHC ν_μ samples in FGD1 and FGD2 split using proton and photon tagging



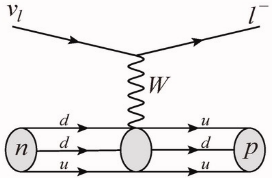
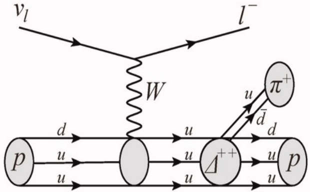
ND280 samples for this analysis → 22 samples

- New FHC ν_μ samples in FGD1 and FGD2 split using proton and photon tagging

- Improves the predictions of CCQE & 2p2h interactions.
- Test of whether cross-section modelling improvements are sufficient to describe the near detector data.
- CC-Photon sample -> primarily DIS and resonant interactions with π^0 in the final state. Allows near detector constraint of the multi-ring signal events in the far detector.
- Photon tag also improves the purity of the other samples such that constraints on CCQE and CC RES $1\pi^+$ can also be improved.



6 Far detector samples at SK

Interaction	Visible Topology	Mode
$\nu_l, \bar{\nu}_l$ CCQE, $l = \mu, e$ 	➢ 1 ring μ–like ➢ 1 ring e–like	ν and $\bar{\nu}$
ν_l CC RES $1\pi^+$, $l = e, \mu$ 	➢ 1 ring e–like + 1 decay electron (π^+ is below the Cherenkov threshold) ➢ Multi-ring $1\mu^- + 1\pi^+ + 1$ or 2 decay electrons $1\mu^- + 2$ decay electrons	ν only

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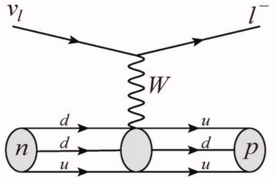
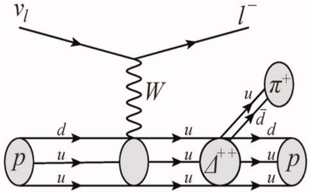
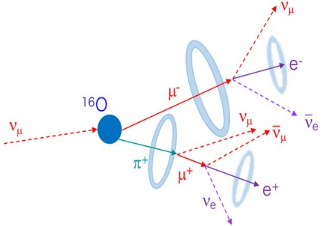
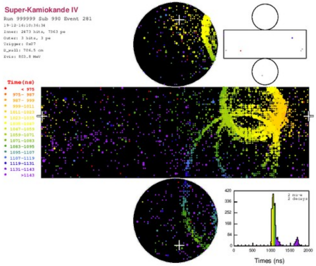
$\nu_l, \bar{\nu}_l$ CCQE, $l = \mu, e$ 	➢ 1 ring μ–like ➢ 1 ring e–like	ν and $\bar{\nu}$
ν_l CC RES $1\pi^+$, $l = e, \mu$ 	➢ 1 ring e–like + 1 decay electron (π^+ is below the Cherenkov threshold) ➢ Multi-ring $1\mu^- + 1\pi^+ +$ 1 or 2 decay electrons $1\mu^-$ + 2 decay electrons	ν only

Multi-ring ν_μ charged current $1\pi^+$ events in SK

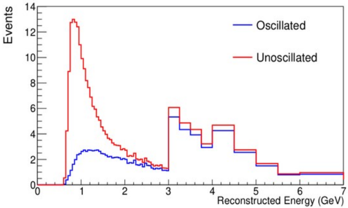


$1\mu^- + 1\pi^+ + 1$ or 2 decay electrons
$1\mu^- + 2$ decay electrons

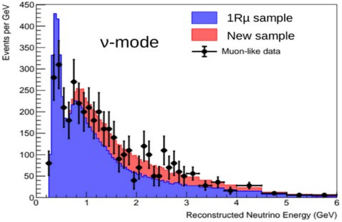


Event display for a MR MC event with 2 decay e

- NEW! Included for the first time in T2K oscillation analysis.
- Parent E_ν ~1.2 GeV → oscillation effect is still present.

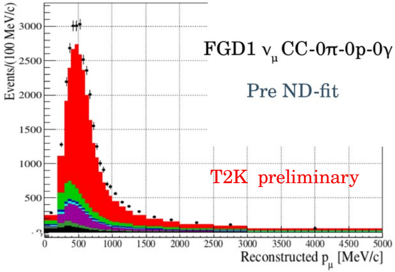


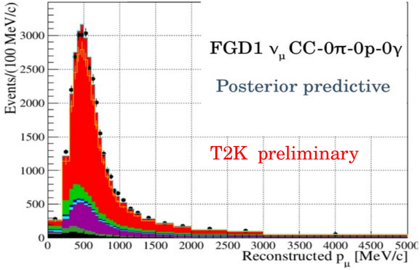
- ~30% increase in ν_μ-like events: Sensitive to θ_{23} & $|\Delta m^2_{32}|$.

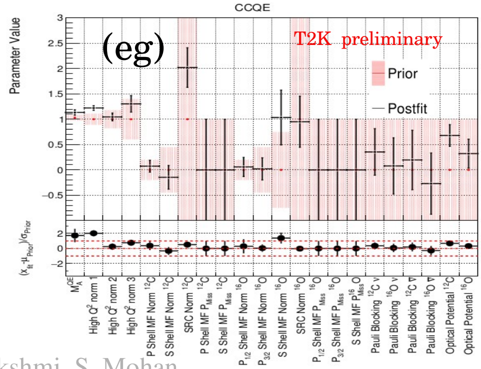


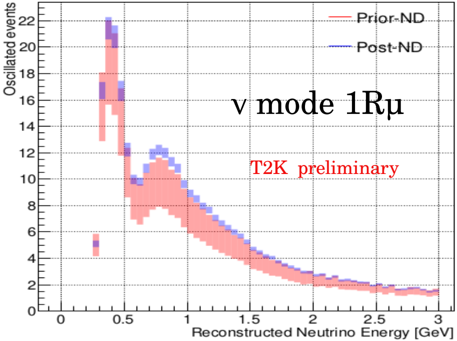
Results from the fits

After ND fit - Smaller uncertainties on flux and cross section parameters



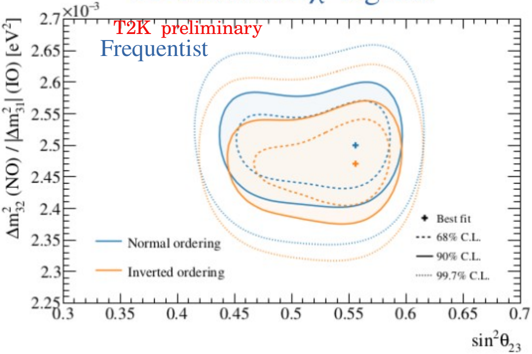




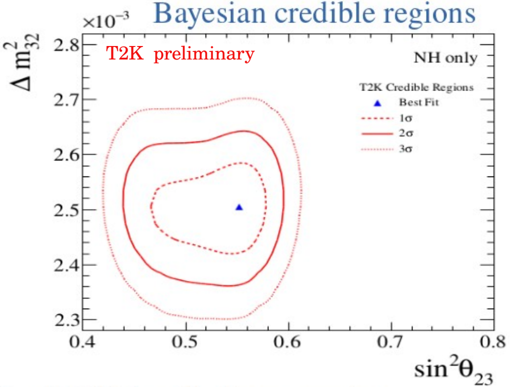


Oscillation parameters from T2K fits – θ_{23} , Δm^2_{32} (| Δm^2_{31} |)

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



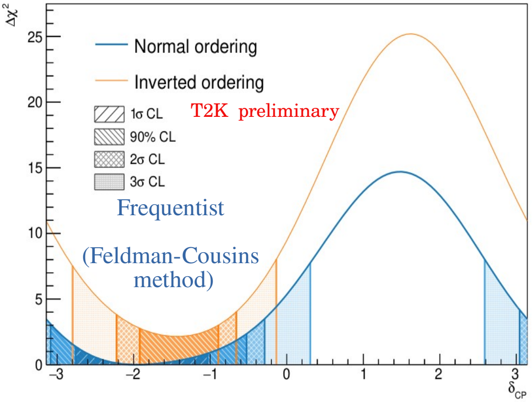
Bayesian credible regions

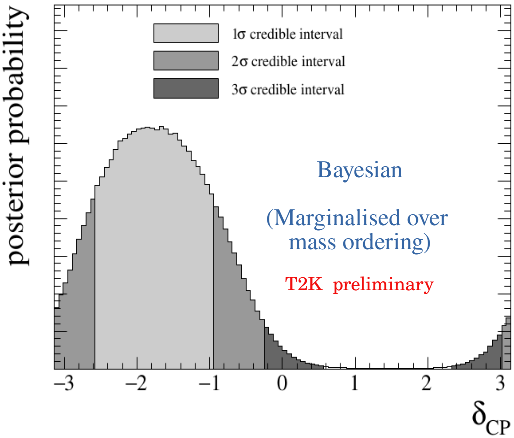


With the constraint $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$ on θ_{13} from reactor anti-neutrino experiments.

- Best fit in the upper octant
- Lower octant still allowed within 68% CL

CP phase – With the constraint $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$ from reactor anti-neutrino experiments



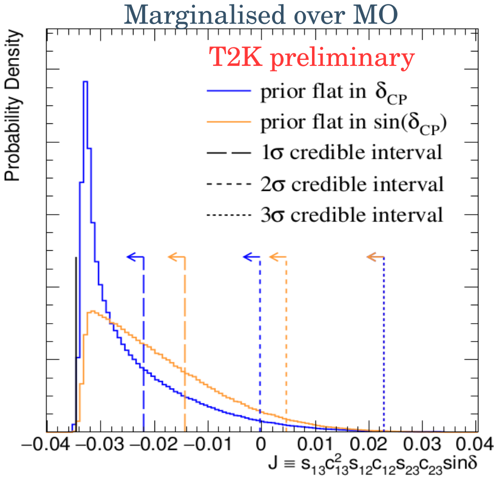


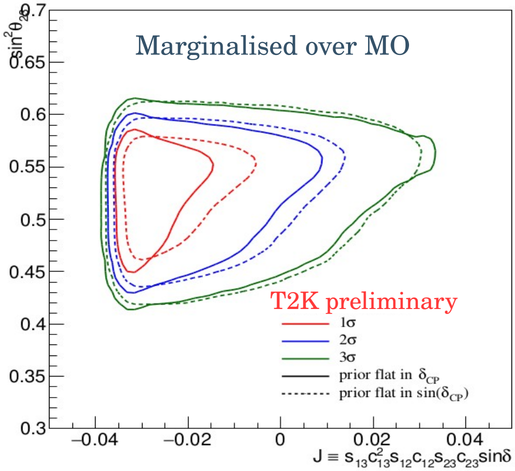
- CP-conserving values of δ=0 and δ=π are outside of 90% CL intervals
- Effect of alternative interaction model tested → did not find biases that would change this conclusion.

Jarlskog invariant $J \equiv s_{13}c_{13}^2s_{12}c_{12}s_{23}c_{23}\sin\delta$

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

Constraint $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$ on θ_{13} from reactor anti-neutrino experiments





- 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.

θ_{23} octant and mass ordering preferences

T2K only	Posterior probabilities $\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.24	0.39	0.63
IH ($\Delta m^2_{32} < 0$)	0.15	0.22	0.37
Sum	0.39	0.61	1.000

T2K + reactor θ_{13}	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.20	0.54	0.74
IH ($\Delta m^2_{32} < 0$)	0.05	0.21	0.26
Sum	0.25	0.75	1.000

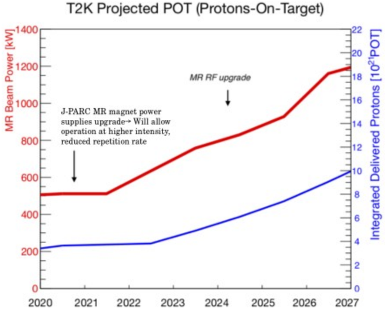
T2K preliminary

Mild (slightly stronger) preference for normal ordering and upper octant, without (with) reactor constraint on θ_{13} → limited significance.

Future plans

- Ongoing joint analyses with SK atmospheric and NovA
  - Access to different L_ν/E_ν → can break degeneracies
- Upgrade of beam, ND280 & SK-Gd → 3σ sensitivity on δ_{CP}

Beam upgrade

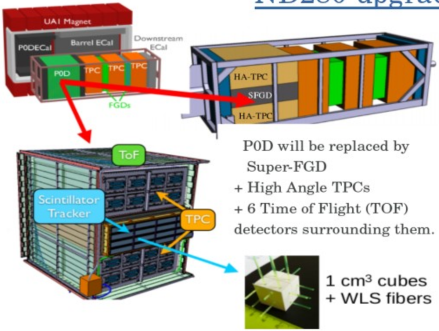


Upgrade of:

- Neutrino beamline to handle higher intensity beam
- Horn power supplies → will allow their operation at ~320 kA

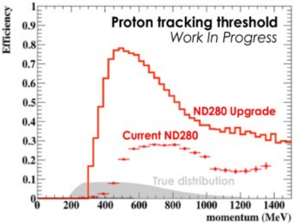
Expected to be ready for operation in early 2023.

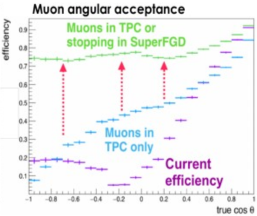
ND280 upgrade



P0D will be replaced by Super-FGD
+ High Angle TPCs
+ 6 Time of Flight (TOF) detectors surrounding them.

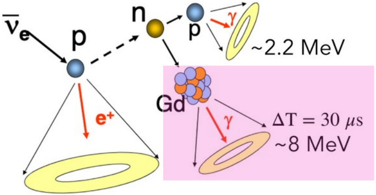
1 cm³ cubes + WLS fibers



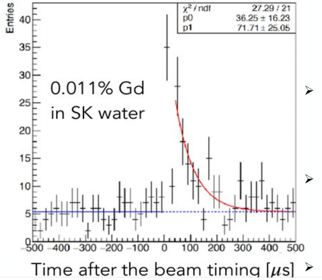


Upgrade of far detector: SK-Gd

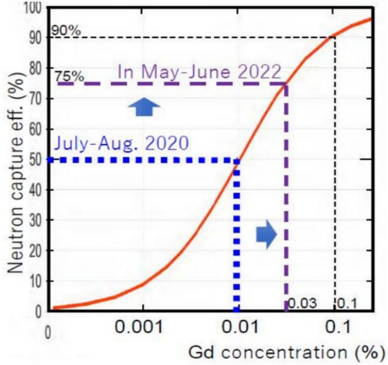
Neutron tagging by addition of Gd



$\bar{\nu}_e$ identification possible by delayed coincidence



Neutron capture efficiency increases with Gd concentraion



- Exponential curve indicates the presence of neutrons in T2K data
- Run 11 data taken with SK-Gd in 2021 (not used for analysis yet)
- Prospect of $\nu/\bar{\nu}$ separation in T2K beam data

Summary

- Sensitivity studies to oscillation parameters are done with existing data:

  - with significant improvements in flux and interaction models
  - addition of proton and photon tagged samples in near detector &
  - a new ν_μ CC multi-ring sample at the far detector

- δ_{CP} from T2K → still favours near-maximal CP violation, ~-π/2.
  CP conservation continues to be excluded at 90% CL.

- Slight preference normal mass ordering (NO) and for upper octant of θ_{23}, but consistent with lower octant and maximal values.

- Ongoing T2K+NOvA and T2K+SK atmospheric joint analyses
  → can address degeneracies.

- Beam, near detector, and far detector all are being upgraded to enable enhanced sensitivity to cross sections and oscillation parameters.


Umut Kose
Shigeki AOKI (...
Atsumu Suzuki
Lukas Berns
Yoshinari Hayato
Yuma kawamura
Hokuto Kobaya...
Noë Roy
Christophe Bro...
Jiayu Ji
Lucio Ludovici
Eric D. Zimmer...
M Nishida
Dave Wark
Takuji Arihara
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Takashi Honjo
kikawa
Atsuko Ichikawa
Sophie King
T. Nakadaira (I...
Kenji Yasutome
Celeste
Van Nguyen
Marcela Batkie...
Yohei Noguchi
Robert Kurjata
Kimihiro Okum...
Guillaume Eurin
Dung Nguyen
Neil McCauley
Masaki Kawaue
Tristan Doyle
Kouki Nagai
Antonio
Hokuto Kobaya...
Maitrayee Man...
Davide Sgalab...
M Nishida
Holin, Anna (ST...
Dung Nguyen
Tomasz Wachala
Kouki Nagai

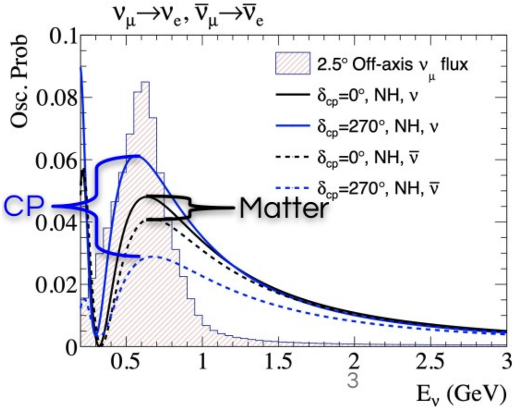
Thank you!

Backup

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2))$$
$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$
$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta_{CP}\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$
$$+4S_{12}^2 C_{13}^2(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta_{CP})\sin^2\Phi_{21}$$
$$-8C_{13}^2 S_{13}^2 S_{23}^2(1 - 2S_{13}^2)\frac{aL}{4E_\nu}\cos\Phi_{32}\sin\Phi_{31},$$

$$\Phi_{ji} = \Delta m_{ji}^2 L/4E_\nu$$

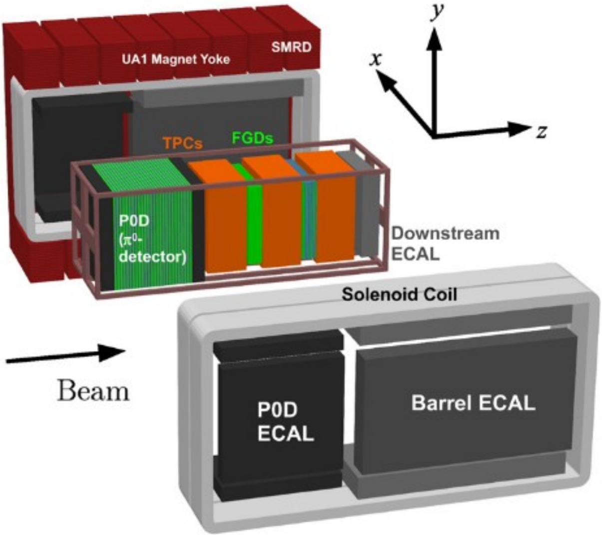
$$a \equiv 2\sqrt{2}G_F n_e E_\nu$$
$$= 7.56 \times 10^{-5}[\text{eV}^2](\frac{\rho}{[g/cm^3]})(\frac{E_\nu}{[GeV]})$$



Lakshmi .S. Mohan

ND280 detector

- UA1 magnet
- SMRD
- P0D
- FGDs
- TPCs
- ECAL



- UA1 magnet: To measure momenta & determine the sign of charged particles produced by neutrino interactions.
- Side muon range detector (SMRD): records muons escaping with high angles w.r.to the beam direction and measures their momenta.
- (PØD): to measure NC process $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0 + X$ on H_2O target.
- Fine grained detector (FGD): Two FGDs provide target mass for neutrino interactions as well as tracking of charged particles coming from the interaction vertex.

  FGD1 – scintillator
  FGD2 – water + scintillator

- Time Projection Chambers (TPCs)

  - Has good tracking resolution.

  - To determine the number and orientations of charged particles traversing the detectors → helps selecting high purity samples of different ν interactions.

  - Measure momenta of charged particles produced by ν interactions elsewhere in the detector. → Helps to determine the event rate as a function of E_ν for the neutrino beam, before oscillations.

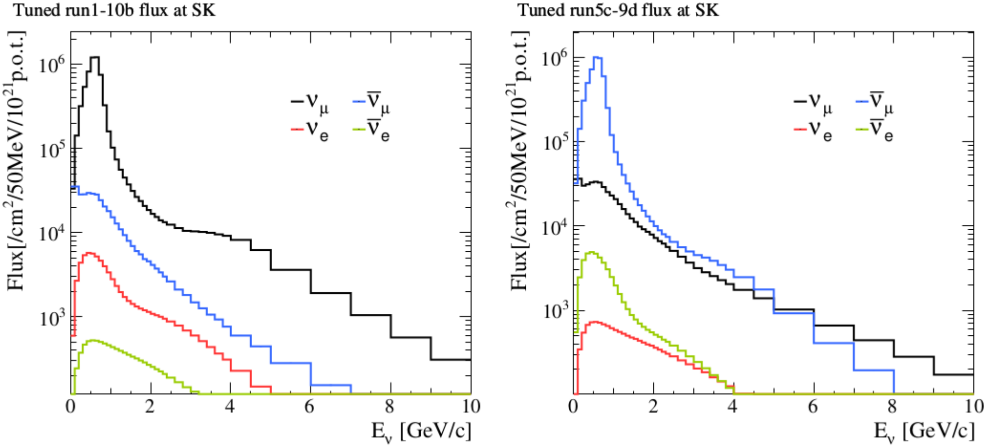
  - PID using ionization left by each particle + momentum → Helps to determine the relative abundance of ν_e in the beam.

- Electromagnetic calorimeter (ECAL)

  - Detection of photons and measurement of their energy & direction.

  - Detection of charged particles and the extraction of information (e/μ/π separation); reconstruction of π^0s.

Fluxes at the far detector



List of the 22 ND280 samples

Sample
FGD1 FHC CC0π-0p-0γ
FGD1 FHC CC0π-Np-0γ
FGD1 FHC CC1π-0γ
FGD1 FHC CC-Other-0γ
FGD1 FHC CC-Photon
FGD1 RHC CC0π
FGD1 RHC CC1π
FGD1 RHC CC-Other
FGD2 RHC CC0π
FGD2 RHC CC1π
FGD2 RHC CC-Other

FGD2 FHC CC0π-0p-0γ
FGD2 FHC CC0π-Np-0γ
FGD2 FHC CC1π-0γ
FGD2 FHC CC-Other-0γ
FGD2 FHC CC-Photon
FGD1 RHC BKG CC0π
FGD1 RHC BKG CC1π
FGD1 RHC BKG CC-Other
FGD2 RHC BKG CC0π
FGD2 RHC BKG CC1π
FGD2 RHC BKG CC-Other

Uncertainty on the number of events in each SK sample broken by error source **before** BANFF fit.

Error source (units: %)	1R FHC	1R RHC	MR FHC $CC1\pi^+$	1Re FHC	1Re RHC	1Re FHC $CC1\pi^+$	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

Uncertainty on the number of events in each SK sample broken by error source **after** the BANFF fit.

Error source (units: %)	1R FHC	1R RHC	MR FHC $CC1\pi^+$	1Re FHC	1Re RHC	1Re FHC $CC1\pi^+$	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

Process	CC	NC
QE	$\nu_l\, n \to l^-\, p$ $\bar{\nu}_l\, p \to l^+\, n$	$\nu_l\, p \to \nu_l\, p\,;\ \nu_l\, n \to \nu_l\, n$ $\bar{\nu}_l\, p \to \bar{\nu}_l\, p\,;\ \bar{\nu}_l\, n \to \bar{\nu}_l\, n$
RES	$\nu_l\, p \to l^-\, p\, \pi^+\,;\ \bar{\nu}_l\, p \to l^+\, p\, \pi^-$ $\nu_l\, n \to l^-\, n\, \pi^+\,;\ \bar{\nu}_l\, n \to l^+\, n\, \pi^-$ $\nu_l\, n \to l^-\, p\, \pi^0\,;\ \bar{\nu}_l\, p \to l^+\, n\, \pi^0$	$\nu_l\, p \to \nu_l\, n\, \pi^+\,;\ \bar{\nu}_l\, p \to \bar{\nu}_l\, n\, \pi^+$ $\nu_l\, n \to \nu_l\, p\, \pi^-\,;\ \bar{\nu}_l\, n \to \bar{\nu}_l\, p\, \pi^-$ $\nu_l\, p \to \nu_l\, p\, \pi^0\,;\ \bar{\nu}_l\, p \to \bar{\nu}_l\, p\, \pi^0$ $\nu_l\, n \to \nu_l\, n\, \pi^0\,;\ \bar{\nu}_l\, n \to \bar{\nu}_l\, n\, \pi^0$
DIS	$\nu_l\, N \to l^-\, X\,;\ \bar{\nu}_l\, N \to l^+\, X$	$\nu_l\, N \to \nu_l\, X\,;\ \bar{\nu}_l\, N \to \bar{\nu}_l\, X$

MC true momentum threshold for counting visible particles

Particle	Momentum [MeV/c]
$e^{\pm}$	10
γ	20
$\mu^{\pm}$	120.495
π^{+}	159.169
π^{0}	0
Proton	1070.03
Other charged particles	Cherenkov threshold

For other particles $p_{\text{Cherenkov Threshold}} = m_0/0.882925$

Energy reconstruction

$$E_{rec}^{\nu \mathrm{CCQE-like}} = \frac{2E_l(M_n - E_b) - M_l^2 + 2M_nE_b - E_b^2 + M_p^2 - M_n^2}{2(M_n - E_b - E_l + P_l \cos\theta_l)}$$

E_b = 27 MeV binding energy

Energy of outgoing muon

Δ_{++} mass

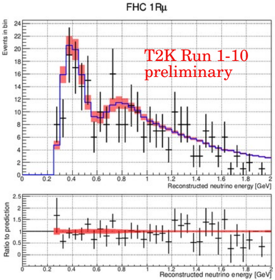
Proton mass

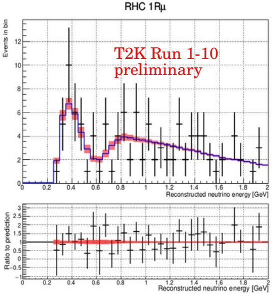
Muon mass

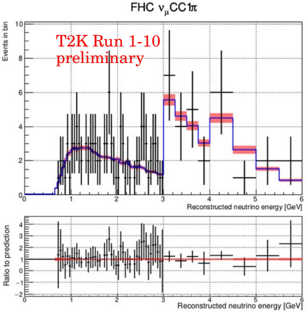
$$E_{\mathrm{rec}}^{\nu_\mu \mathrm{CC}\Delta^{++}} = \frac{2M_pE_\mu + M_{\Delta^{++}}^2 - M_p^2 - M_\mu^2}{2\left(M_p - E_\mu + |p_\mu| \cos\theta_\mu\right)}$$

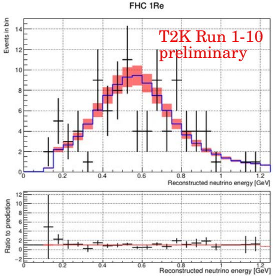
Momentum and angle of outgoing muon

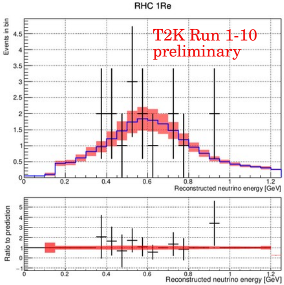
SK samples - MaCh3

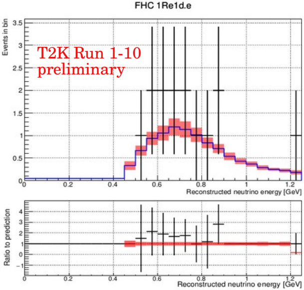






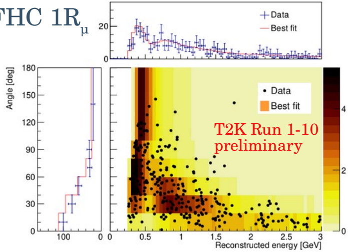




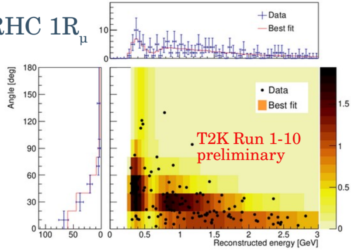


SK samples - ptheta

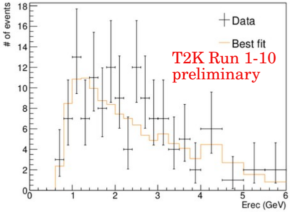
FHC $1R_\mu$



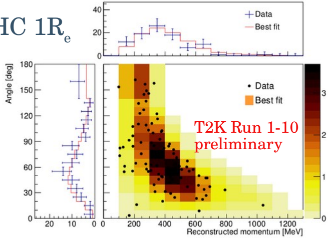
RHC $1R_\mu$



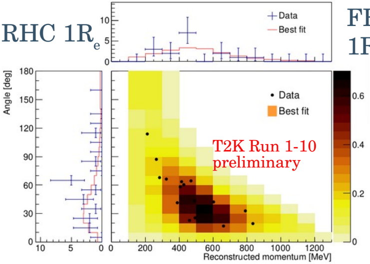
FHC MR CC ν_μ $1\pi^+$



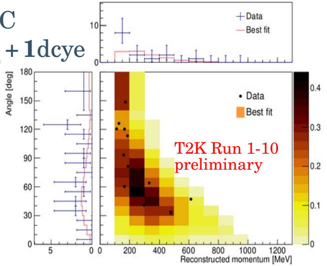
FHC $1R_e$



RHC $1R_e$



FHC $1R_e$ + 1dcye



Event rates at SK using best fit oscillation parameters from the simultaneous ND + FD fit using Bayesian framework with reactor constraint on θ_{13}. SK-MC is scaled to POT with flux tune, BANFF/NIWG post-fit re-weight also applied to compare to the number of events.

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	$\delta_{CP} = -2.18$	Data
FHC 1Rμ	373.617	372.977	373.576	374.339	374.023	318
RHC 1Rμ	143.227	142.891	143.229	143.593	143.433	137
FHC 1Re	101.809	85.601	70.123	86.324	99.163	94
RHC 1Re	17.171	19.509	21.610	19.273	17.503	16
FHC 1Re1de	9.970	8.664	7.045	8.451	9.618	14
FHC ν_μ CC1π^+	115.383	114.884	115.357	115.864	115.662	134

Best fit

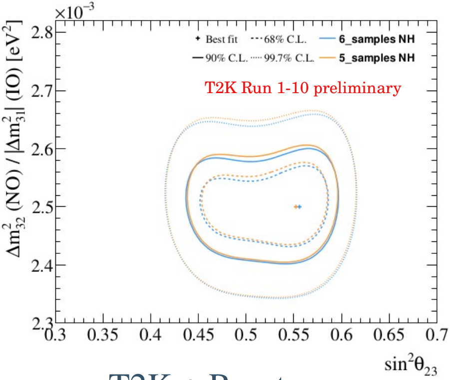
Event rates at SK using best fit oscillation parameters from consecutive fitter framework with reactor constraint on θ_{13}. SK-MC is scaled to POT with flux tune, BANFF/NIWG post-fit re-weight also applied to compare to the number of events.

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	$\delta_{CP} = -2.18$	Data
FHC 1Rμ	376.863	376.164	376.822	377.644	377.303	318
RHC 1Rμ	144.292	143.945	144.294	144.668	144.503	137
FHC 1Re	102.279	86.2003	70.7227	86.8013	99.6123	94
RHC 1Re	17.286	19.6316	21.7309	19.3853	17.6153	16
FHC 1R ν_e CC1π^+	10.0223	8.72417	7.1075	8.4057	9.669	14
FHC MR ν_μ CC1π^+	115.994	115.489	115.968	116.482	116.278	134

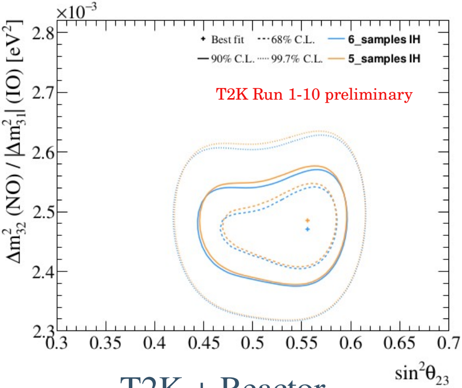
T2K Run 1-10 preliminary

Best fit

Effect of the new MR ν_μ CC1π^+ sample on oscillation parameters

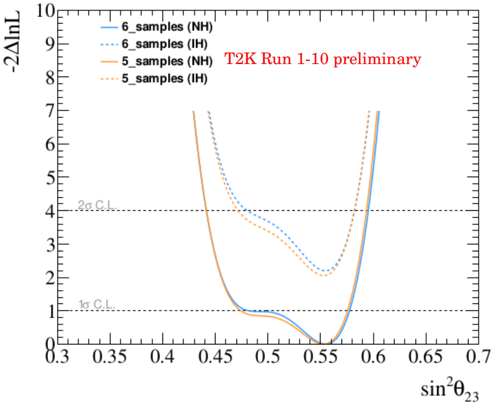


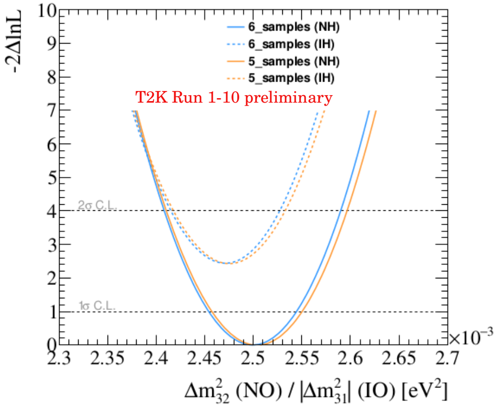
T2K + Reactor



T2K + Reactor

T2K + Reactor



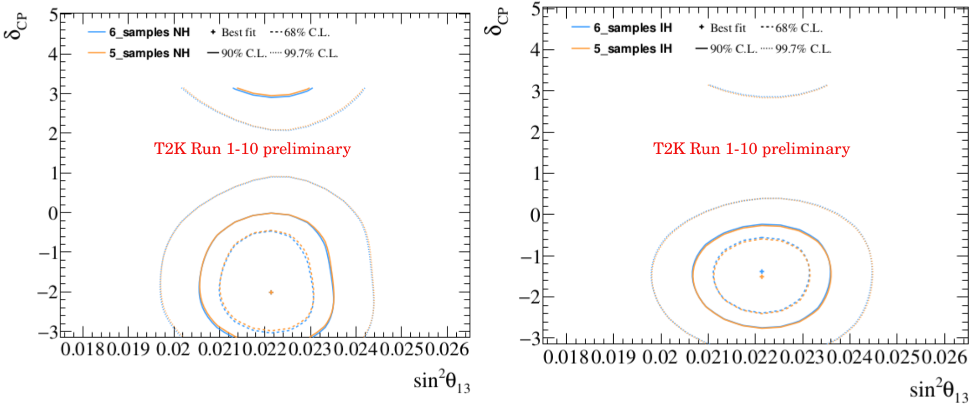


1σ range of Δm^2_{32}

- 5 samples : $[2.454, 2.544] \times 10^{-3}\,eV^2$
- 6 samples : $[2.455, 2.550] \times 10^{-3}\,eV^2$

~5% improvement in the 1σ error of Δm^2_{32}

T2K + Reactor



New MR sample is sensitive to ν_μ disappearance. → Not much effect on appearance parameters.

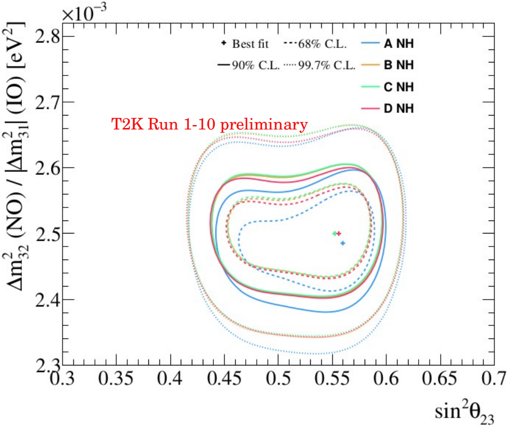
Effect of changes from 2020 results to 2022 results

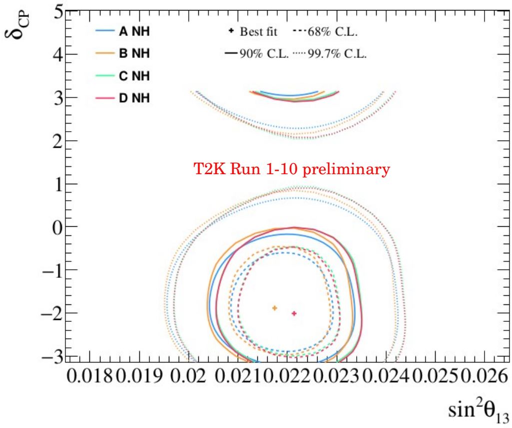
A = OA2020

B = A + new interaction model and new samples in ND fit

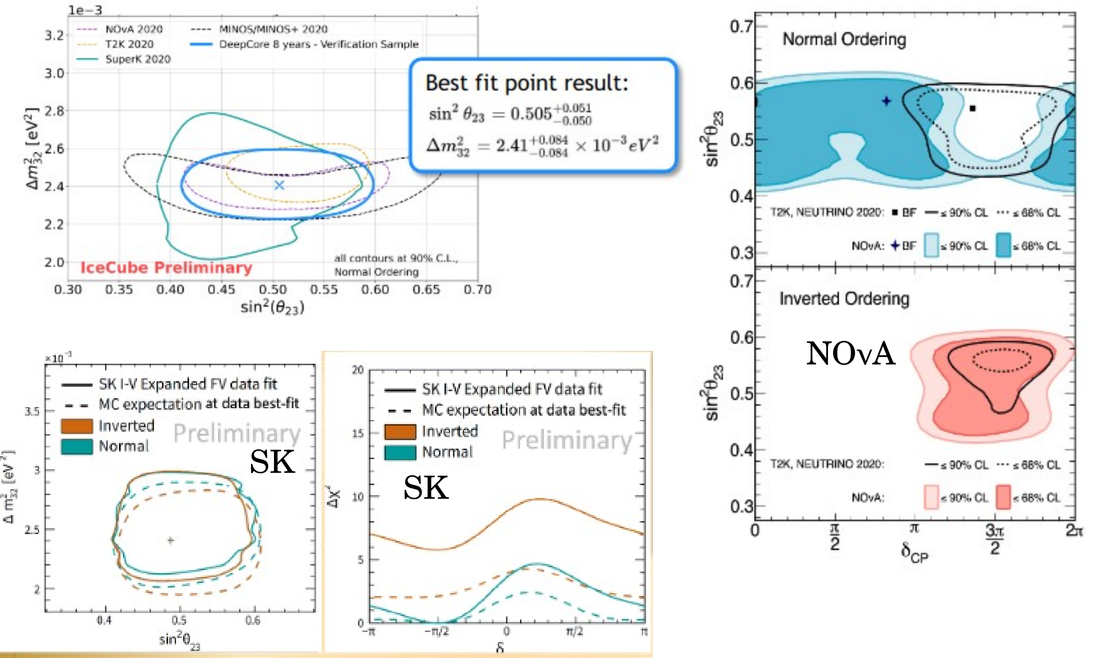
C = B + PDG 2021 constraint on $\sin^2 2\theta_{13}$

D = C + MR ν_μCC1π^+ sample





Results from other experiments – from NuFACT 2022 slides



T2K + NovA joint analysis

- Two LBL experiments with different L, E_ν and detectors
  - Complementary to study oscillations
  - Can break the MO – δ_{CP} degeneracy

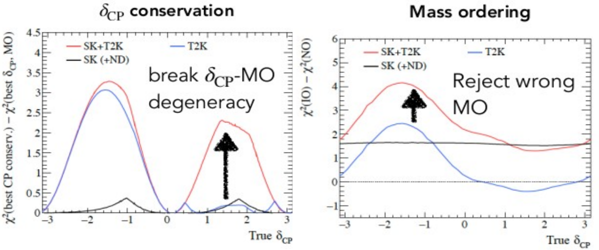
Specification of the experiment	T2K	NOvA
Proton beam energy	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection technology	Water Cherenkov	Segmented liquid scintillator bars
CP effect*	~30%	22%
Matter effect	9%	29%

* Minimum difference of sin(δ_{CP})=0 and ±1, ν & anti-ν

T2K beam + SK atmospheric joint analysis

Atmospheric (anti-)neutrinos → Broader L_ν/E_ν

- More matter effect due to mantle/core resonance
- Sensitivity to mass ordering → can be improved by constraining θ_{23} and δ_{CP} using T2K data
- δ_{CP} independent MO sensitivity from atmospheric samples breaks δ_{CP}- MO degeneracy
- δ_{CP} sensitivity increases if $\delta^{true}_{CP} < 0$ in NO
- Common detector (SK) between the two experiments → need to check effect of correlations between systematics

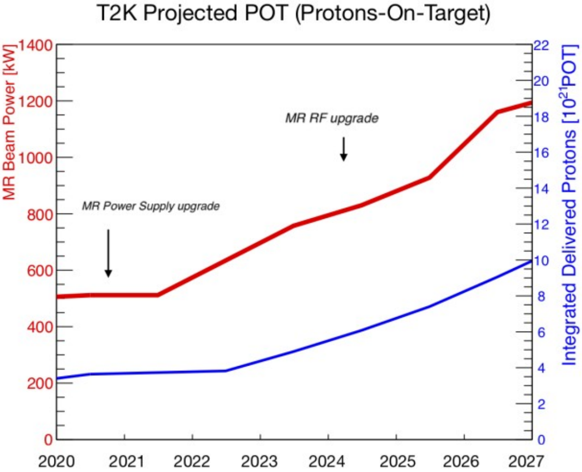


T2K upgrade: of beam, ND280 and SK
3σ sensitivity on δ_{CP}

Beam upgrade

Upgrade of:

- J-PARC main ring magnet power supplies → Will allow operation at higher intensity, reduced repetition rate
- Neutrino beamline to handle higher intensity beam
- Horn power supplies → will allow their operation at ~320 kA
- ~10% increase in ν flux @SK



Expected to be ready for operation in early 2023

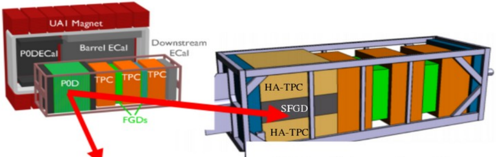
ND280 upgrade

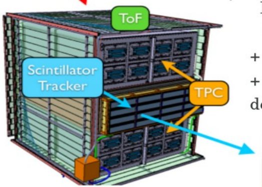
Current ND280

- Limited acceptance for high angle tracks
- Low reconstruction efficiency for the hadronic part of interactions

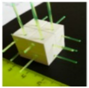
Upgraded ND280

- Super-FGD → Highly segmented; will improve the reconstruction of hadronic part and low momentum leptons
- 2 new High Angle-TPCs → to improve the reconstruction of high angle leptons
- 6 ToF planes → reduce background from outside of Super-FGD

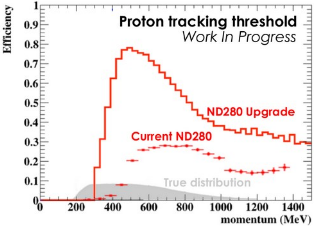


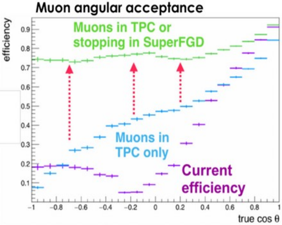


P0D will be replaced by Super-FGD
+ High Angle TPCs
+ 6 Time of Flight (TOF) detectors surrounding them.



1 cm³ cubes
+ WLS fibers





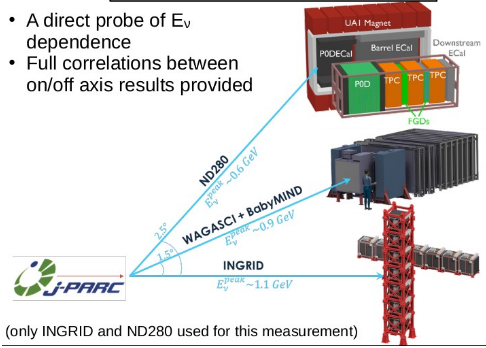
CC0π selection efficiency

Cross section measurements in near detectors at T2K

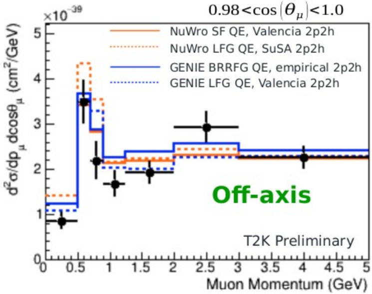
- Focus on "joint" measurements (e.g. C/O, ν_μ/anti-ν_μ, on/off axis)
- Direct probes of physics most relevant for oscillation analyses
- Also perform challenging low rate measurements (eg) (CC coherent on C)

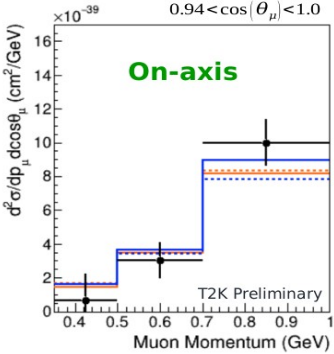
Joint On/Off axis measurements

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



(only INGRID and ND280 used for this measurement)

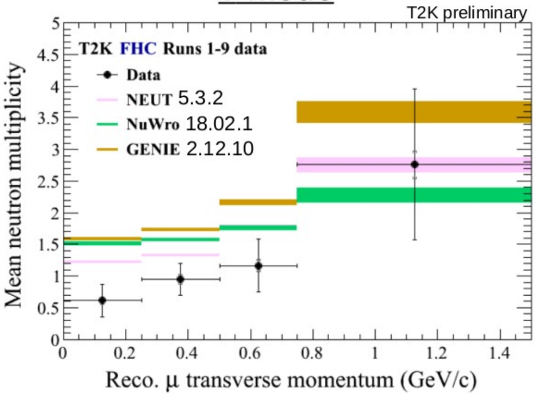




Neutron multiplicities at Super-K

- Use of neutron tagging H_2O Cerenkov detectors → to separate ν/anti-ν, CC/NC ν interaction & to reject backgrounds
- Use in analysis requires good ability to predict neutron productions in neutrino interactions, taking into account FSI and SI.
- No:of neutrons observed in μ-like samples for old (Runs 1-9, Neutrino 2018) oscillation analysis is compared to predictions, using a neural network based tagging algorithm.
- All considered generators were found to over-predict neutron production.

ν-mode



$\bar{\nu}$-mode