

Recent results and perspectives from the experiment



Sophie King

on behalf of the
T2K Collaboration



**New oscillation
analysis results**

Neutrino 2026

**Reconstructed
ND280 upgrade data**



Neutrino Oscillations

Neutrino Oscillations

Flavour eigenstate $|\nu_\alpha\rangle$: Interact
 Mass eigenstate $|\nu_i\rangle$: Propagate } Neutrino oscillation
 → mass and flavour states do not align
 → non-zero masses

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

Oscillations governed by PMNS flavour-mass mixing matrix, U

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

Solar

$$c_{ij} = \cos(\theta_{ij}) \quad \Delta m_{ij}^2 = m_i^2 - m_j^2$$

$$s_{ij} = \sin(\theta_{ij})$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \underbrace{\Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*)}_{\text{Amplitude}} \underbrace{\sin^2\left(\Delta m_{ij}^2 \frac{L}{4E}\right)}_{\text{Distance and Energy}} + 2 \sum_{i>j} \underbrace{\Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*)}_{\text{Amplitude}} \underbrace{\sin\left(\Delta m_{ij}^2 \frac{L}{2E}\right)}_{\text{Distance and Energy}}$$

Amplitude of oscillation: **mixing angles** and **phase**
Distance of oscillation: **squared mass differences** and **Energy**

CP violation

In Vacuum

$\delta_{CP} = 0, \pm\pi \rightarrow$ CP conserved: $P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

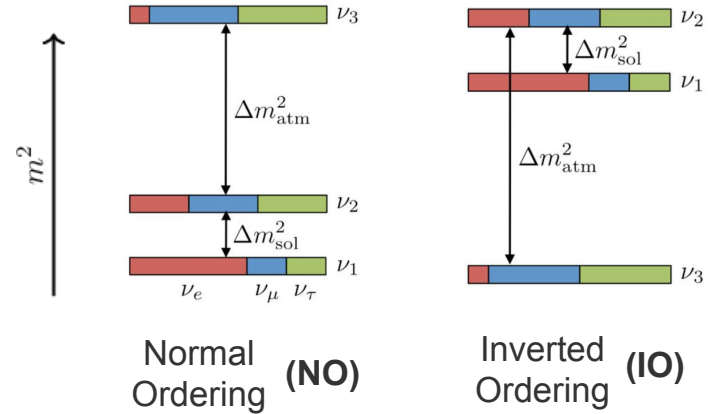
$\delta_{CP} \neq 0, \pm\pi \rightarrow$ **CP violated**: $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Compare oscillation of ν and $\bar{\nu}$ to probe δ_{CP}

Matter effects: Matter consists of electrons

\rightarrow causes additional difference between ν_e and $\bar{\nu}_e$ as they travel through the earth (mimics effect of δ_{CP})

Mass Ordering

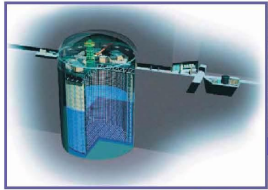


θ_{23} octant:

$\theta_{23} < \pi/4,$ (lower)	$\theta_{23} = \pi/4,$ (maximal)	$\theta_{23} > \pi/4$ (upper)
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T2K



Super-Kamiokande
(ICRR, Univ. Tokyo)

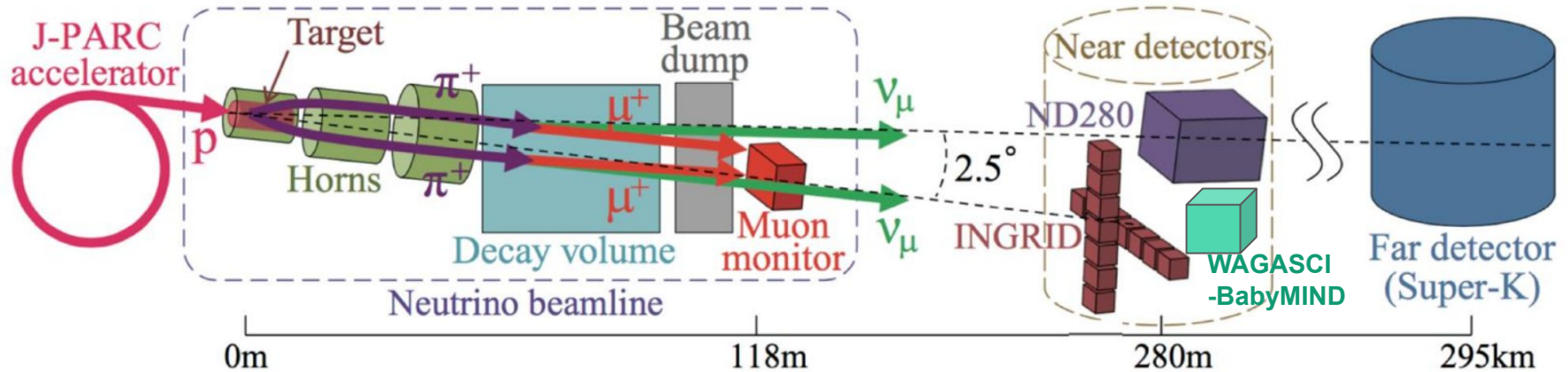


J-PARC Main Ring
(KEK-JAEA, Tokai)



The T2K Experiment

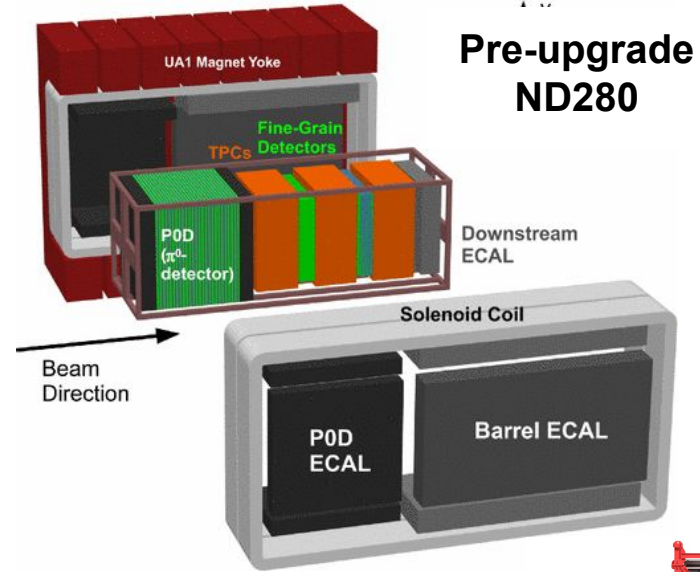
- Accelerator-based neutrino oscillation experiment in Japan



- High intensity **neutrino beam**, predominantly ν_μ ($\bar{\nu}_\mu$)
- On/Off-axis near detectors (280 m): **INGRID**, **ND280**, **WAGASCI-BabyMIND**
- Off-axis far detector (295 km): **Super-Kamiokande**

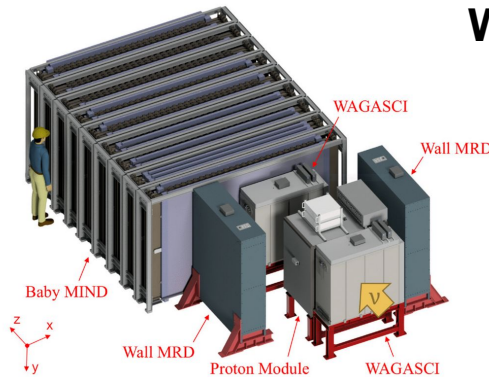
ND280 (Pre-upgrade)

- 2.5° off-axis w.r.t beam
- Magnetised → Charge separation
- **FGDs**: Scintillator and water target
- 3 Time projection chambers (**TPC**)
- Electromagnetic calorimeters (**Ecal**)
- π^0 detector (POD)



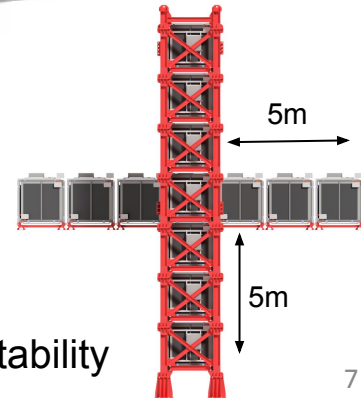
WAGASCI-BabyMIND

- 1.5° off-axis w.r.t beam
- Scintillator, water and iron



INGRID

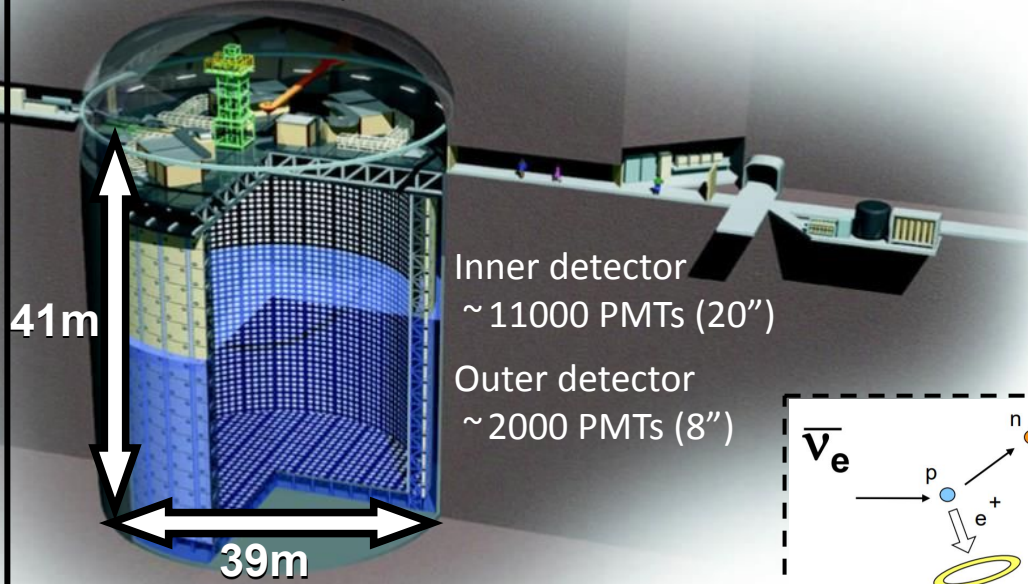
- On-axis, scintillator and iron
- Monitors beam direction, intensity and stability



Super-Kamiokande (SK)

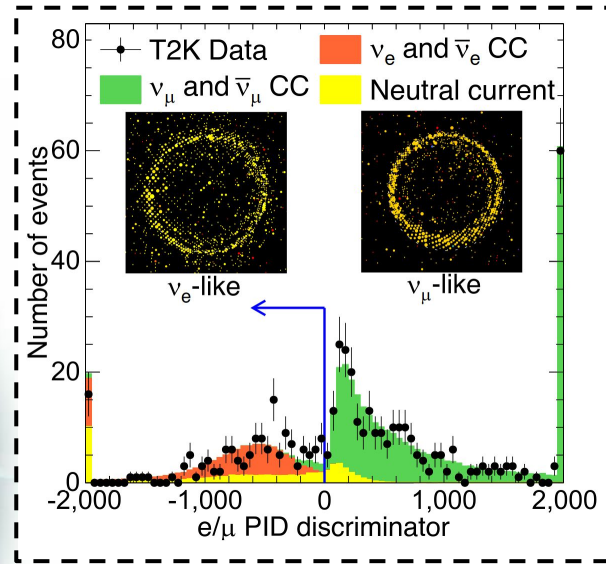
Water Cherenkov Far detector

50 kton of ultra pure water

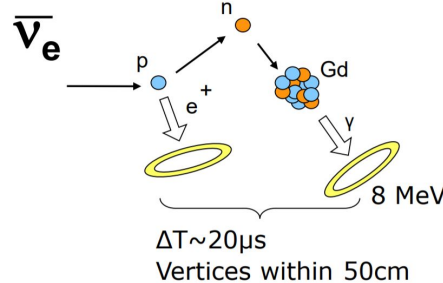


Inner detector
~ 11000 PMTs (20")

Outer detector
~ 2000 PMTs (8")



[Nature 580, 339-344 \(2020\)](#)



Gd added to SK water to
improve neutron tagging

Phase 1: 0.01% Gd

Phase II: 0.03% Gd



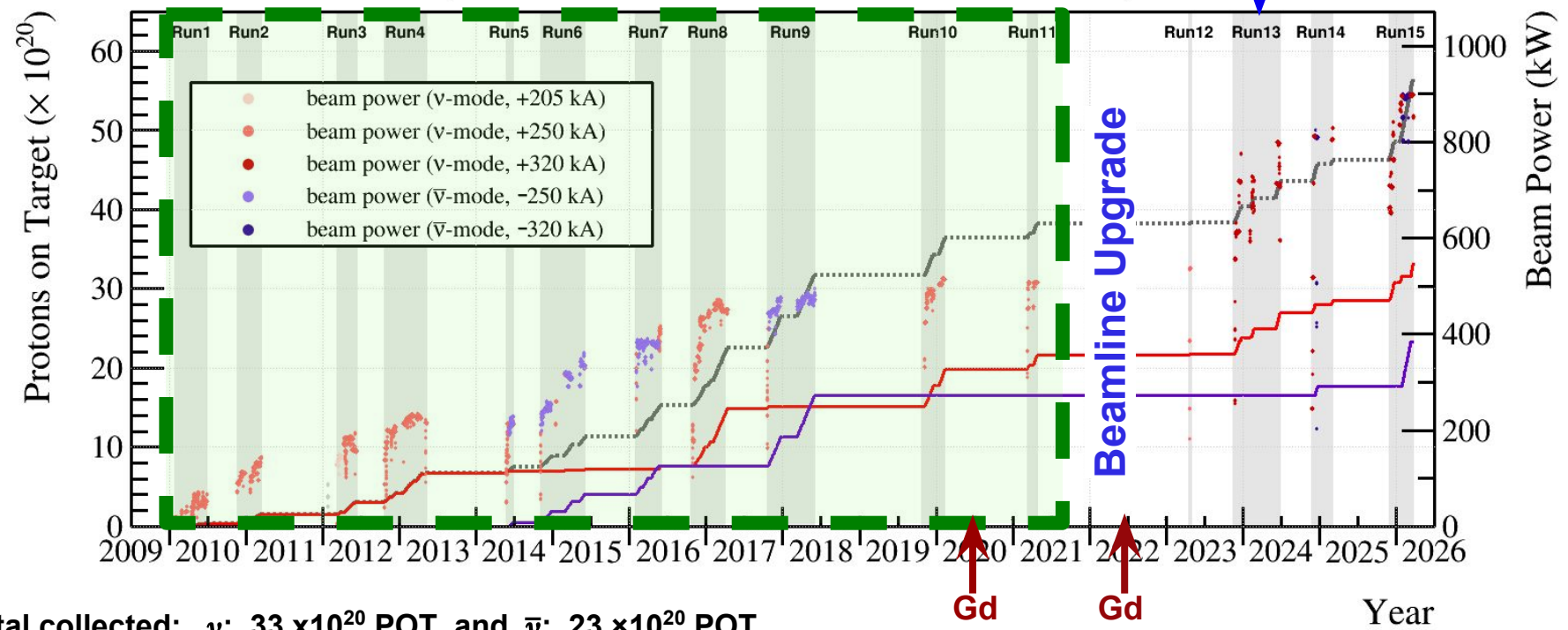
T2K Oscillation Analysis

Collected Data: Protons on Target (POT)

ν : 21×10^{20} POT
 $\bar{\nu}$: 16×10^{20} POT

Data period for these results

..... accumulated POT for physics analysis (total)
 — accumulated POT for physics analysis (ν -mode)
 — accumulated POT for physics analysis ($\bar{\nu}$ -mode)



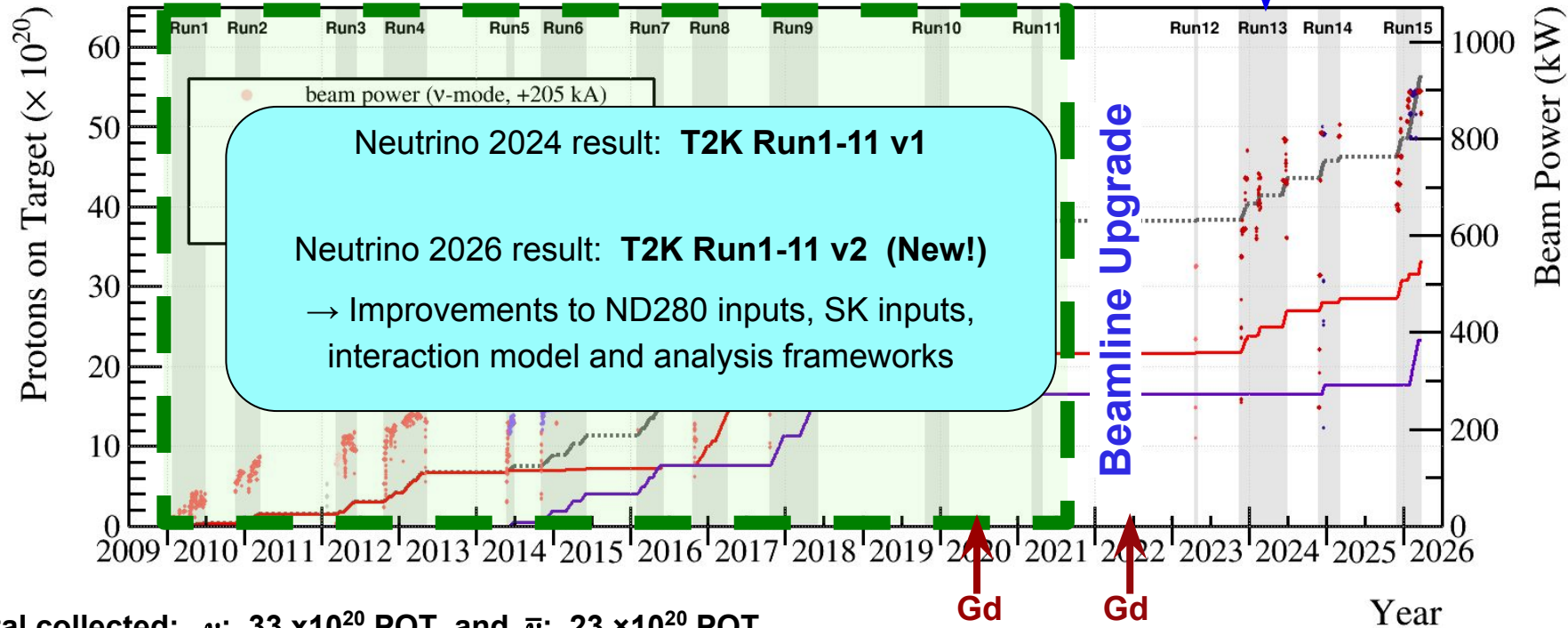
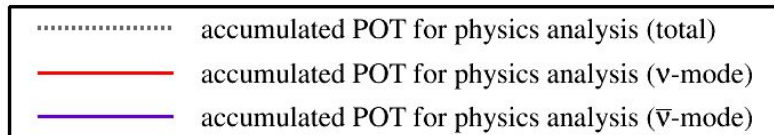
Total collected: ν : 33×10^{20} POT and $\bar{\nu}$: 23×10^{20} POT

Gd 0.01%
 Gd 0.03%

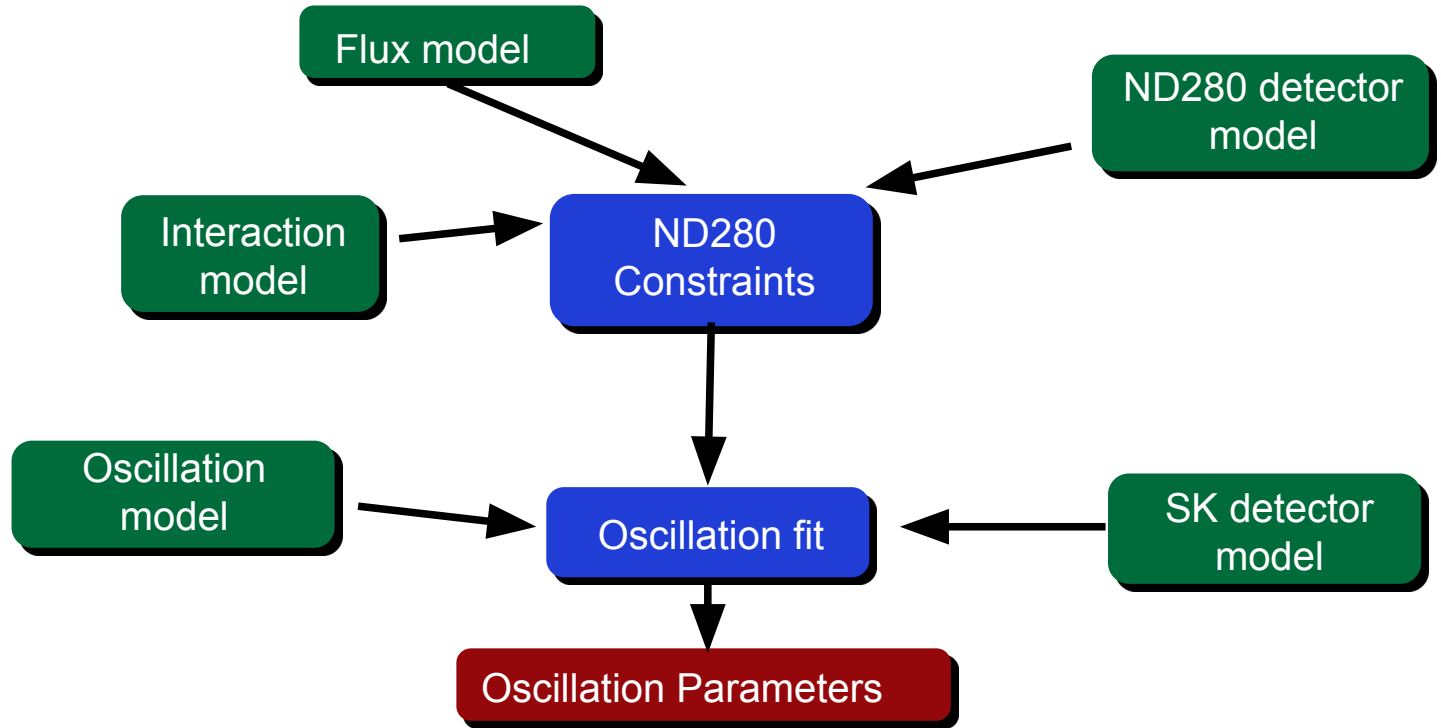
Collected Data: Protons on Target (POT)

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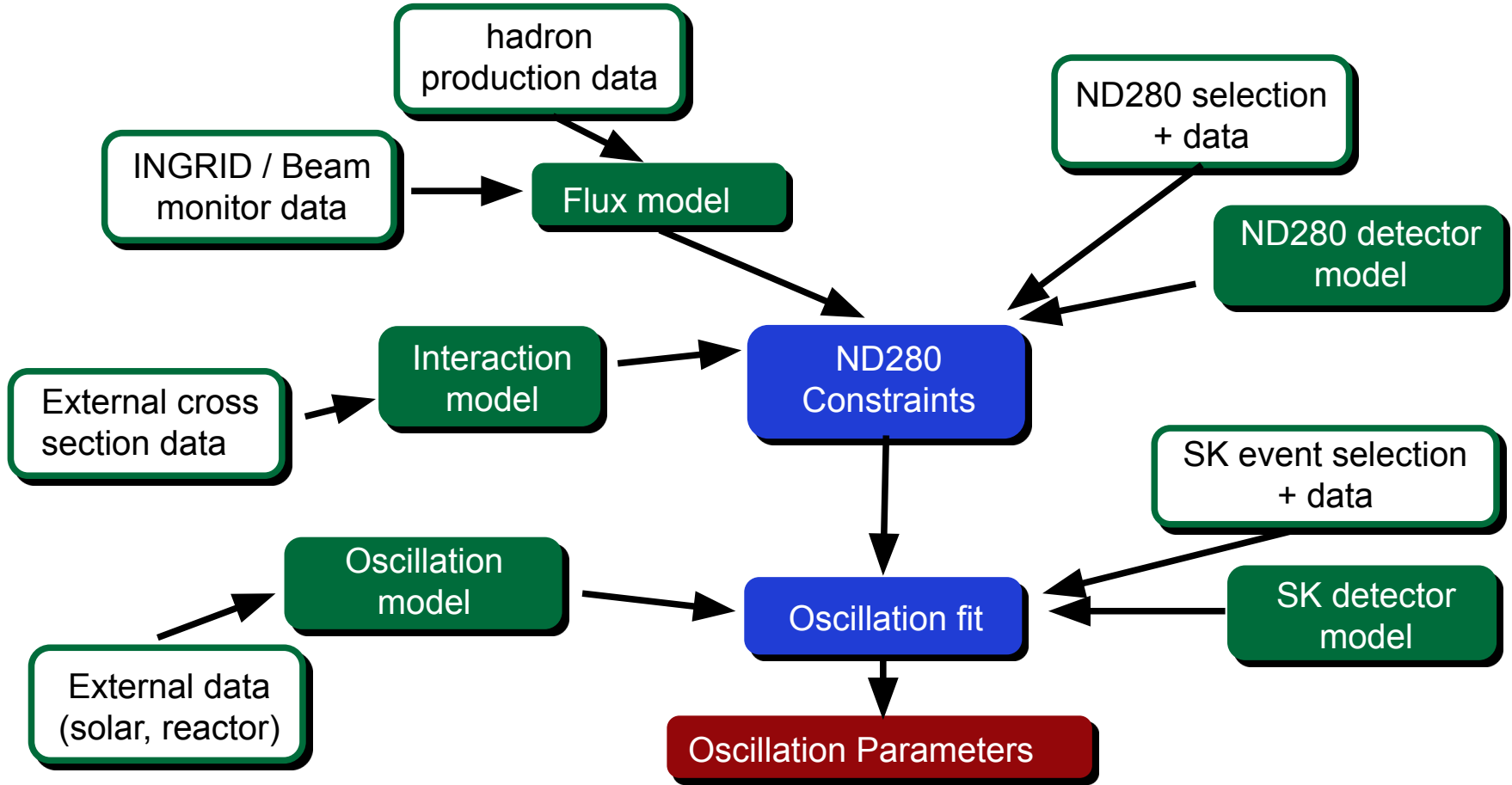
Data period
for these
results



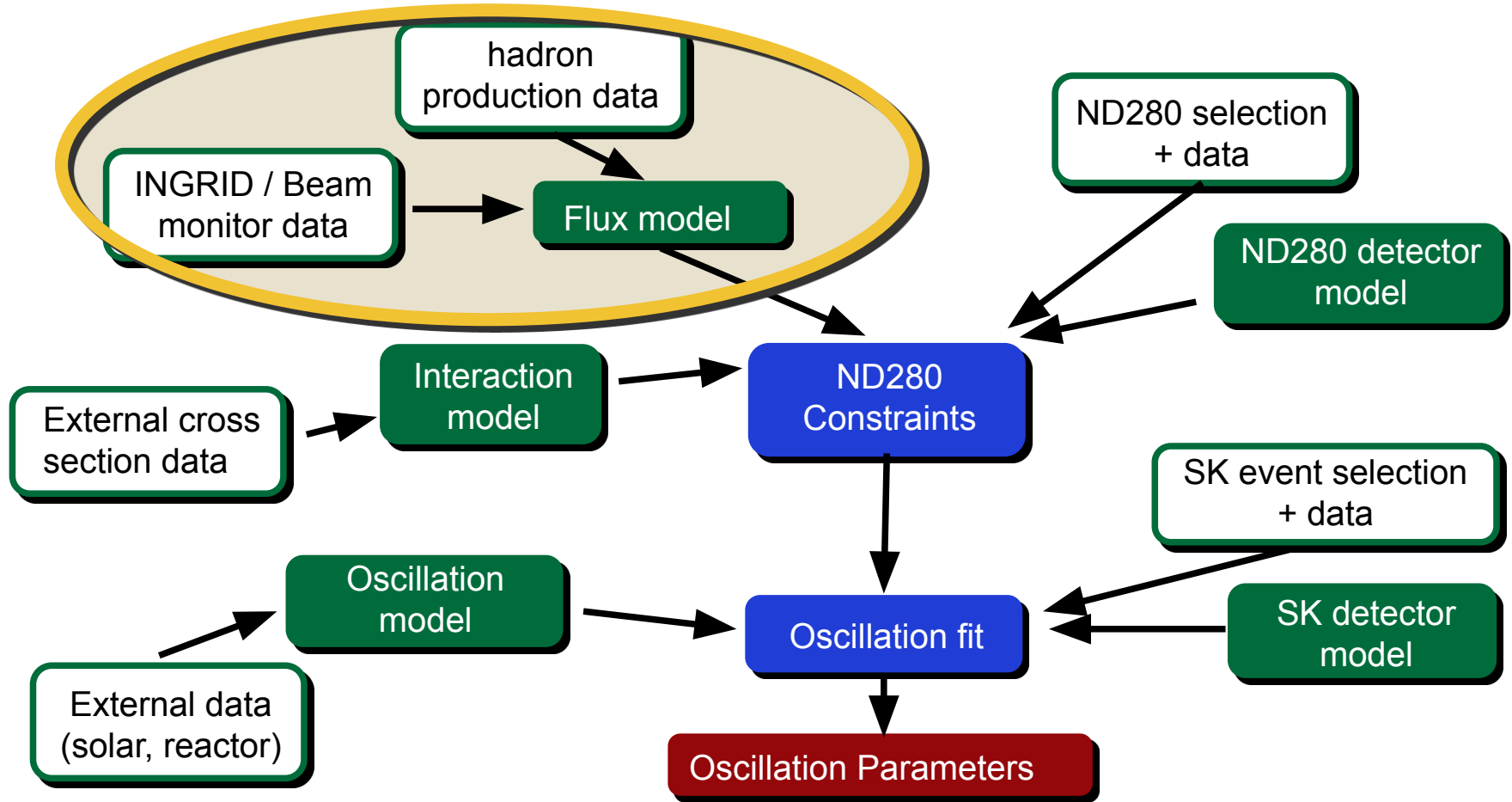
Total collected: ν : 33×10^{20} POT and $\bar{\nu}$: 23×10^{20} POT



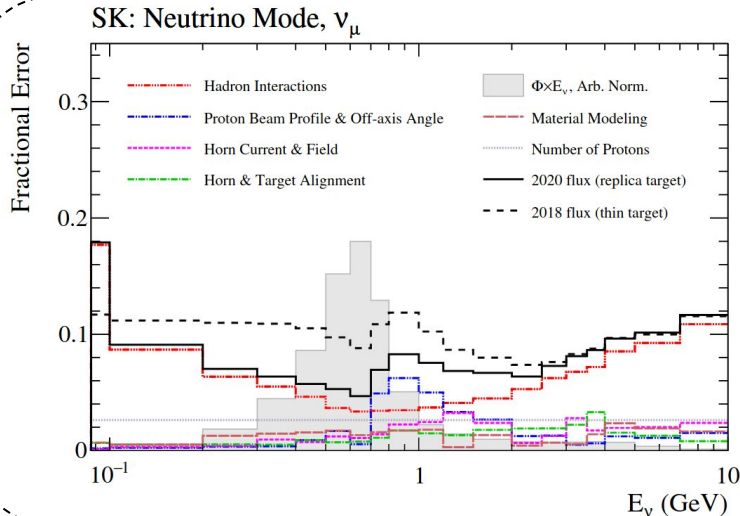
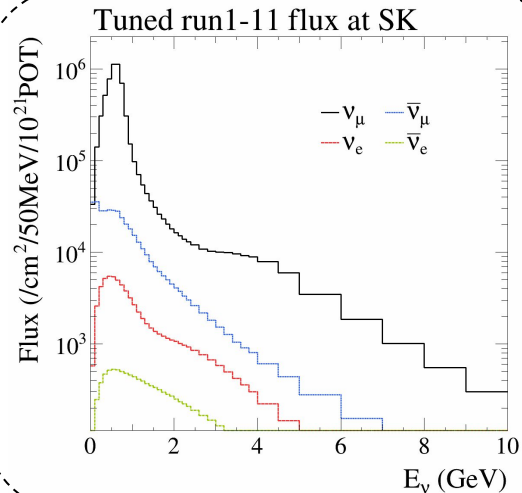
Oscillation Analysis



Oscillation Analysis



- **30 GeV protons** → **graphite** target → charged **hadrons**
- **Electromagnetic horns** select **charge** → hadrons decay to ν or $\bar{\nu}$ depending on charge
- Proton beam monitors measure beam intensity, profile and direction
- **Dominant systematic error due to hadron interaction modelling**
 - Tuned using NA61/SHINE T2K target replica measurements ([Eur.Phys.J. C79 \(2019\) 2, 100](#))
 - Reduces error from $\sim 20\%$ → 5% around the peak
 - Prospects for NA61/SHINE low energy beamline studies to reduce this further



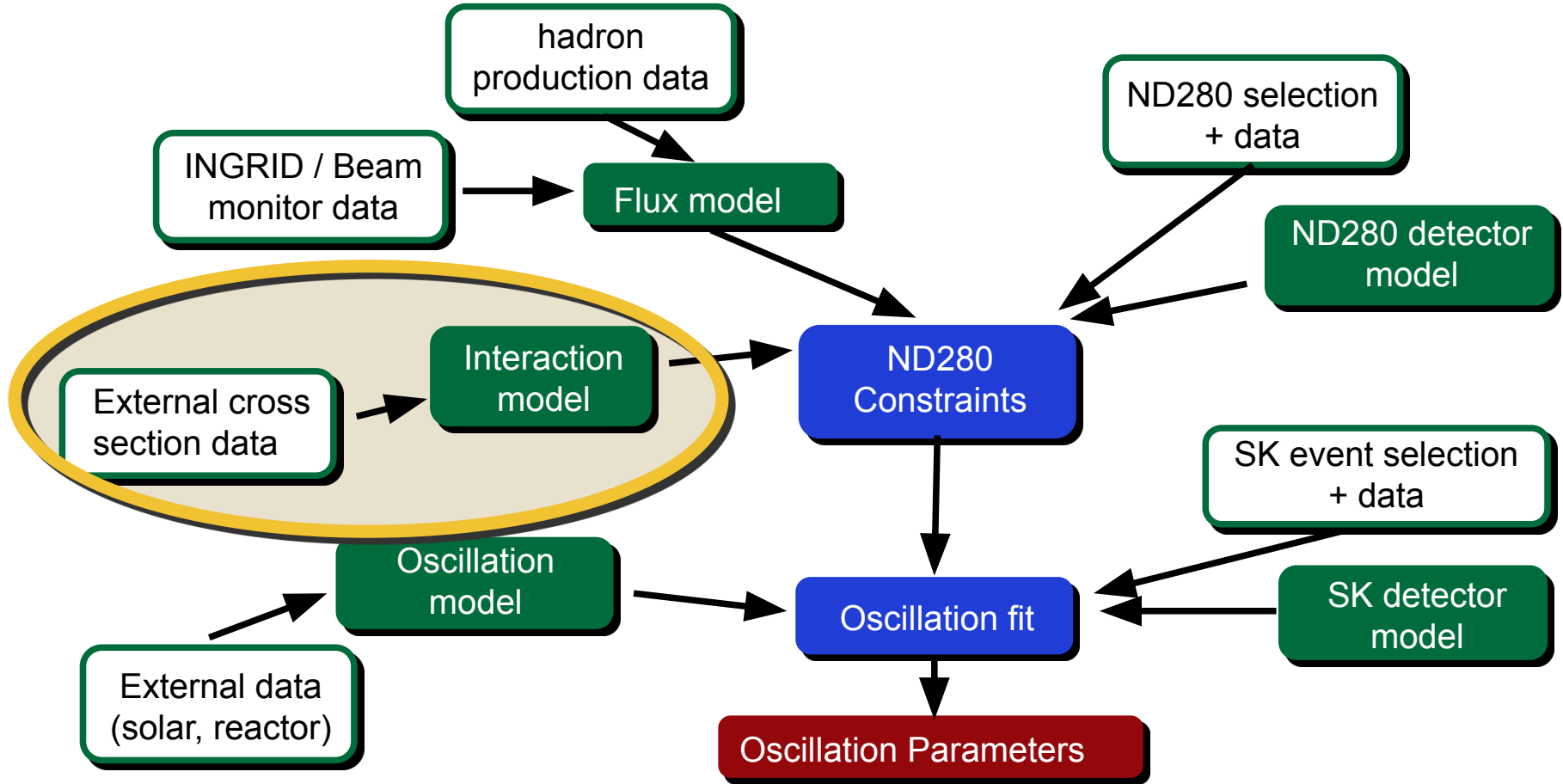
[Poster 1/#74](#)

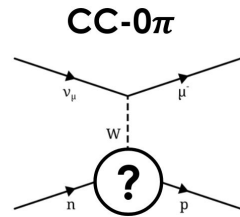
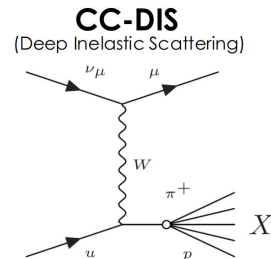
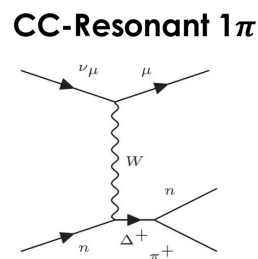
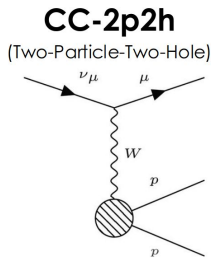
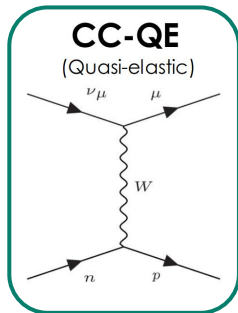
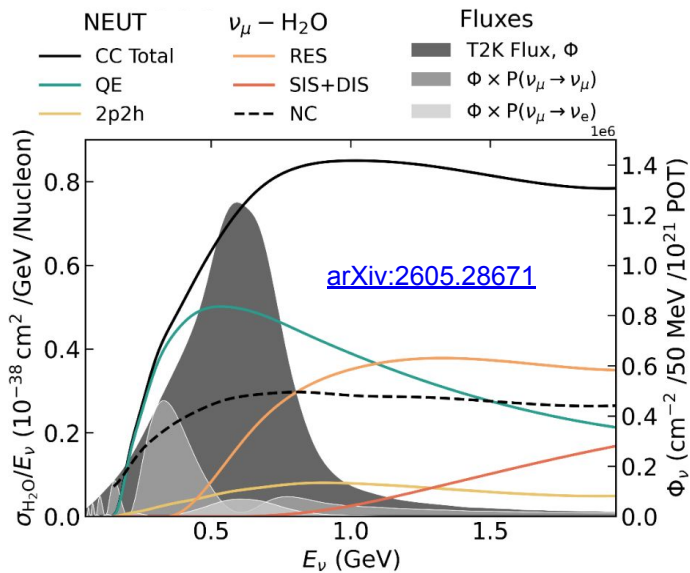
- Y. Nagai -
- Y. Koshio -
NA61 with low
E beamline

[Poster 1/#89](#)

- S. Nishimori -
NA61 with T2K
replica target

Oscillation Analysis





Interactions occur with nucleons bound inside a nucleus \rightarrow **Nuclear effects!**
 e.g. Final State Interactions (FSI) and nucleon-nucleon corrections

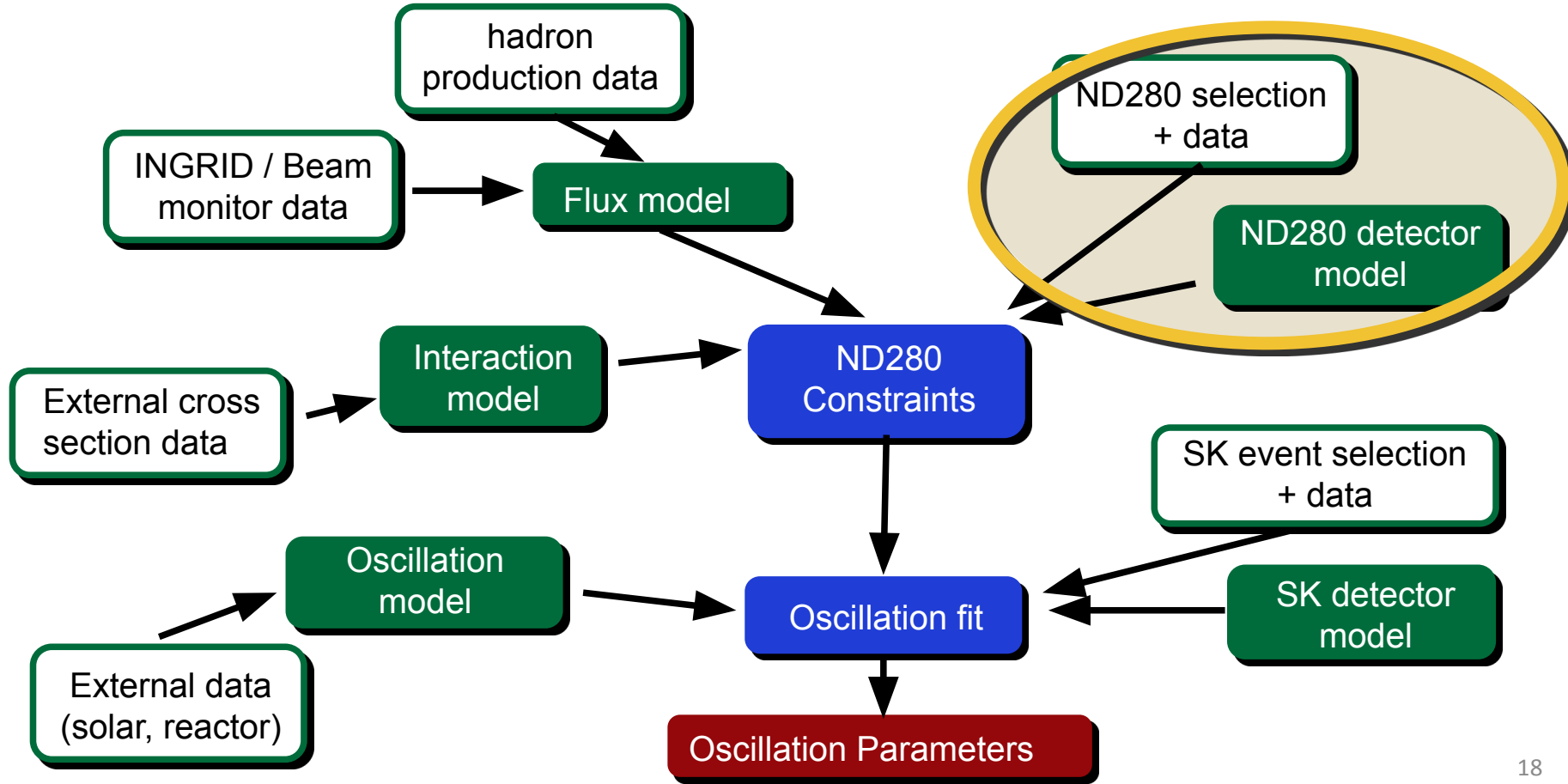
NEUT simulates neutrino-nucleus interactions: [EPJ ST 230, 4469–4481 \(2021\)](https://arxiv.org/abs/2104.04694)

Improved model since Neutrino 2024 (T2K Run 1-11 v1 \rightarrow T2K Run 1-11 v2) :

e.g. overhaul of **low-energy transfer** treatment and improved **nucleon FSI**

Alternate models are used to test **robustness**

Oscillation Analysis



ND280 Inputs

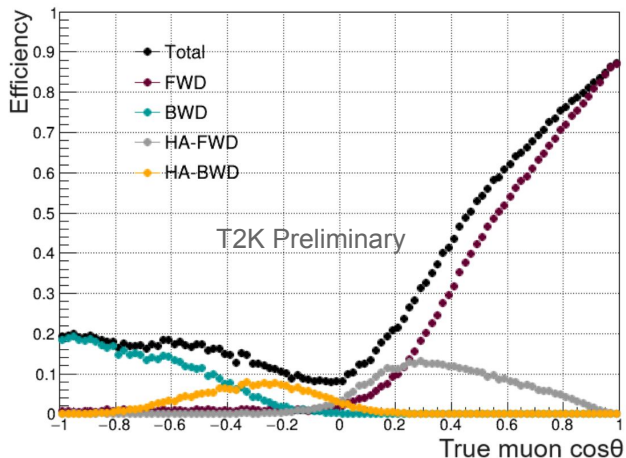
FGD1 (Hydrocarbon)

FGD2 (Hydrocarbon & Water)

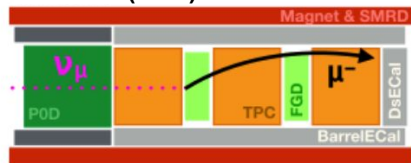
Improvements since Neutrino 2024:

(T2K Run 1-11 v1 → T2K Run 1-11 v2)

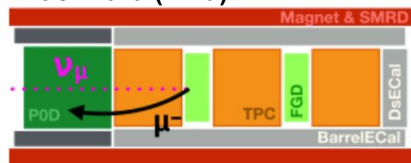
- ν -beam ν_{μ} CC:
Backwards (Bwd) and high-angle (HA)
→ **Improved phase space coverage**
- Improved **reconstruction** techniques
- New parameterization of **detector systematics**



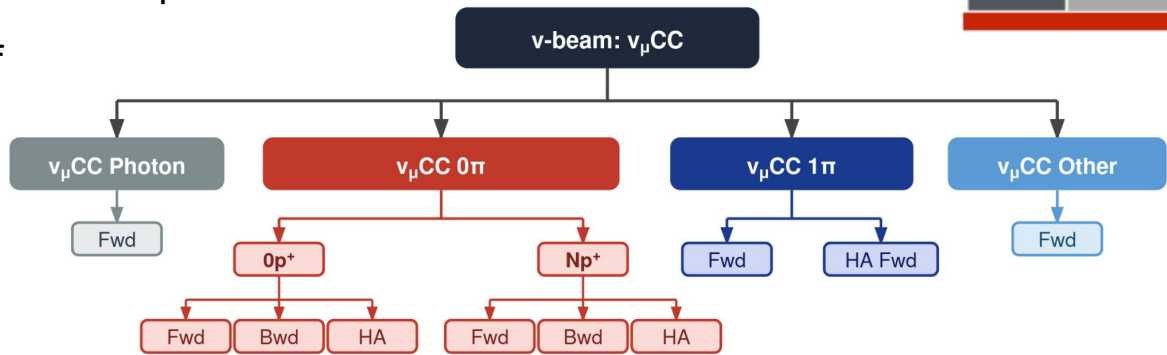
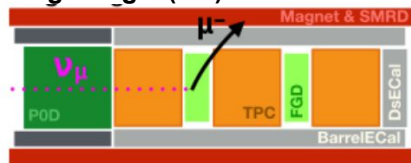
Forward (Fwd)



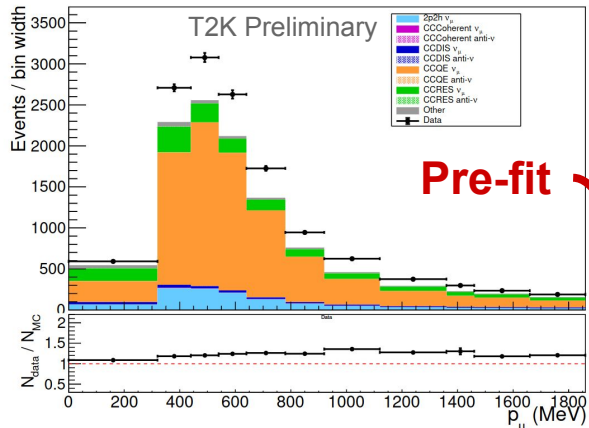
Backward (Bwd)



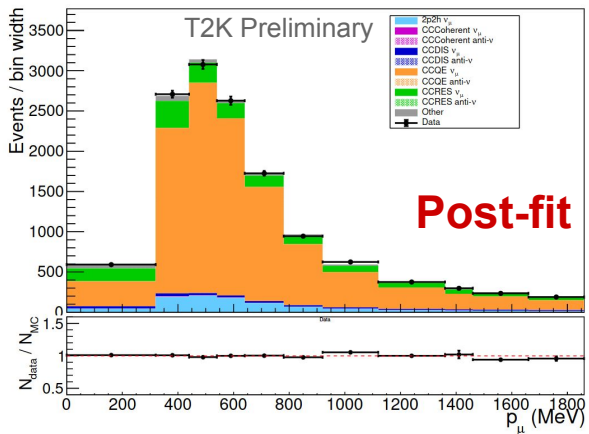
High Angle (HA)



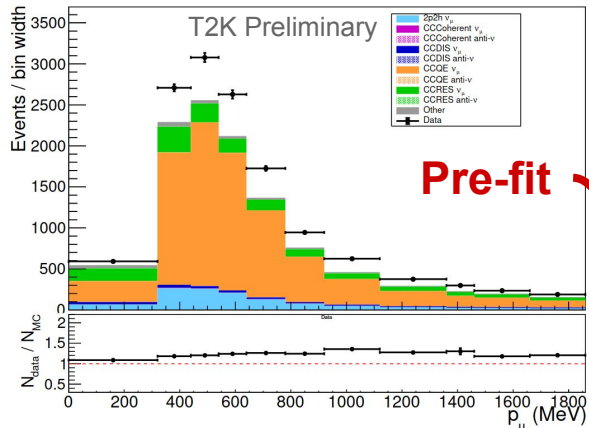
ND280 Data Fit and Constraints



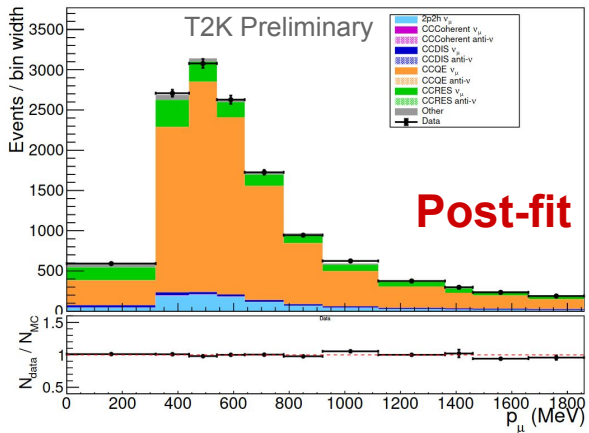
ND280 FGD1 Fwd ν CC $0\pi 0\mu$



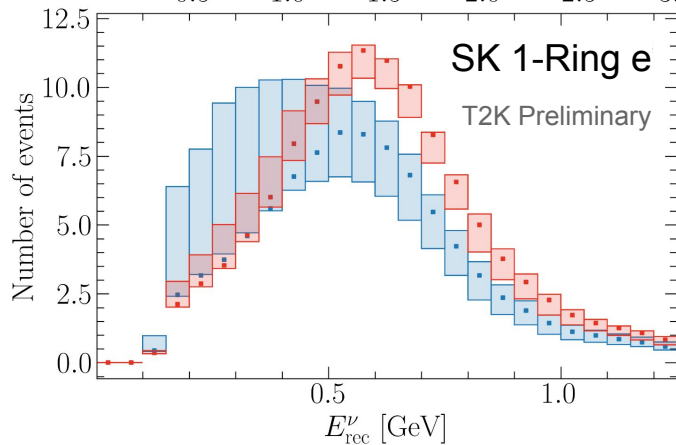
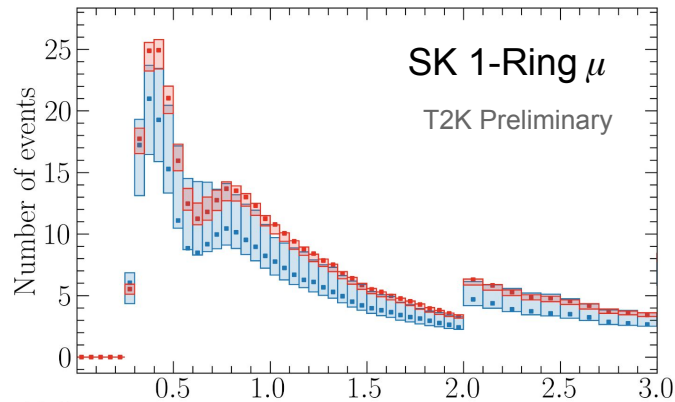
ND280 Data Fit and Constraints



ND280 FGD1 Fwd ν CC $0\pi 0p$



Pre-ND fit ($\mu \pm \sigma$) Pre-ND fit nominal
 Post-ND fit ($\mu \pm \sigma$) Post-ND fit nominal

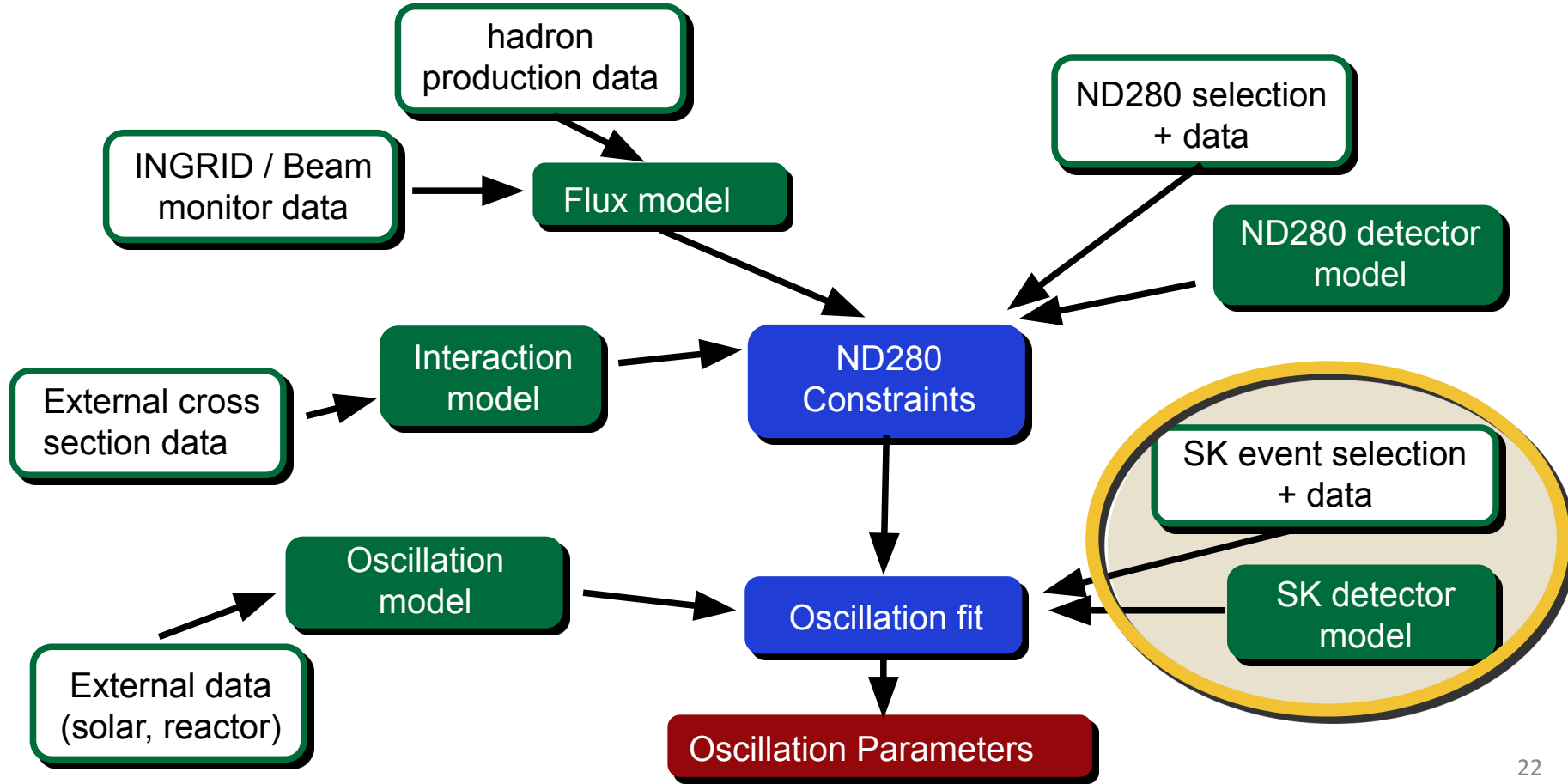


The ND280 fit
 reduces the error
 on the number of
 events selected
 at SK

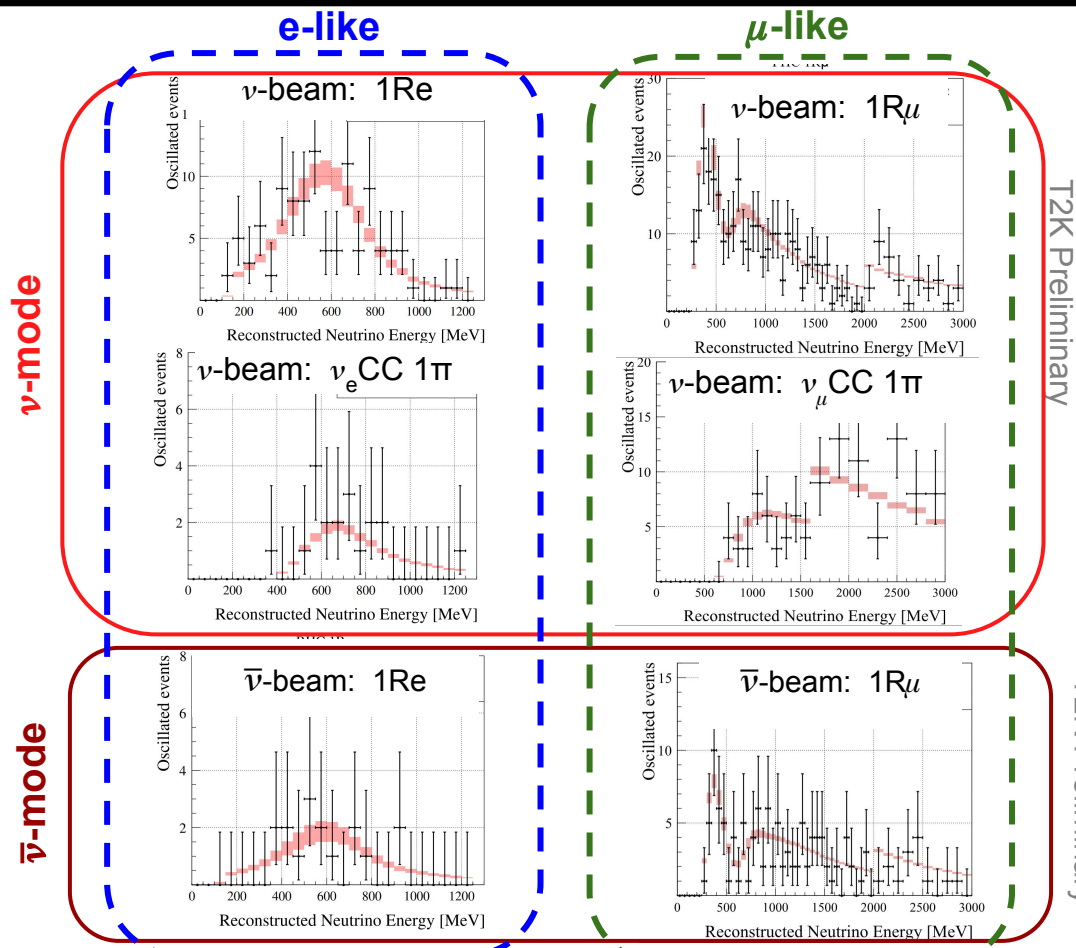
1-Ring μ
 19.2 % \rightarrow 3.7 %

1-Ring e
 20.3 % \rightarrow 5.7 %

Oscillation Analysis



SK Event Samples



Re - Ring electron
R μ - Ring muon

Improvements since Neutrino 2024

(T2K Run 1-11 v1 → T2K Run 1-11 v2)

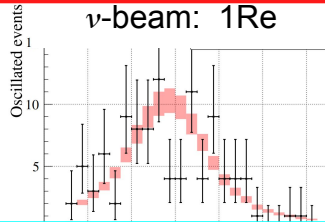
- Updated detector systematics matrix with reduced errors
- Secondary interaction systematics treated separately from detector error matrix
- New multi-ring contribution to ν_e CC 1 π sample

SK Event Samples

ν -mode

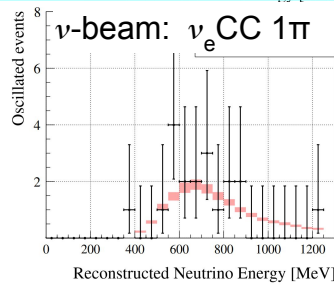
e-like

ν -beam: 1Re



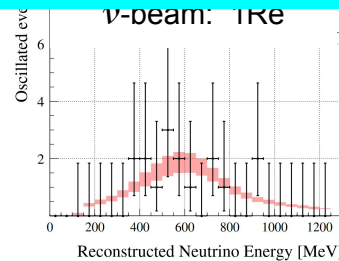
T2K Preliminary

ν -beam: ν_e CC 1 π

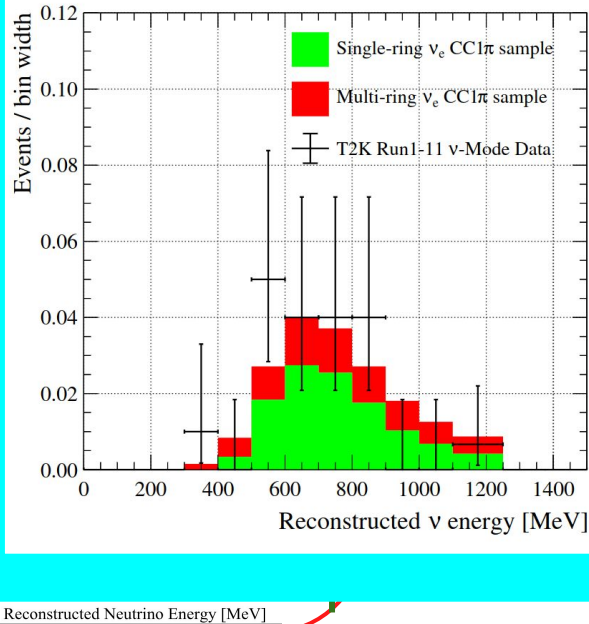


$\bar{\nu}$ -mode

$\bar{\nu}$ -beam: 1Re



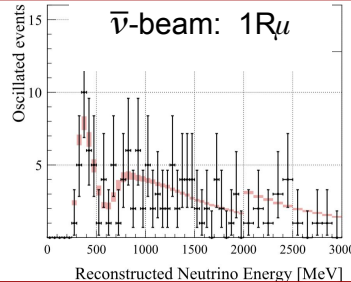
T2K Preliminary



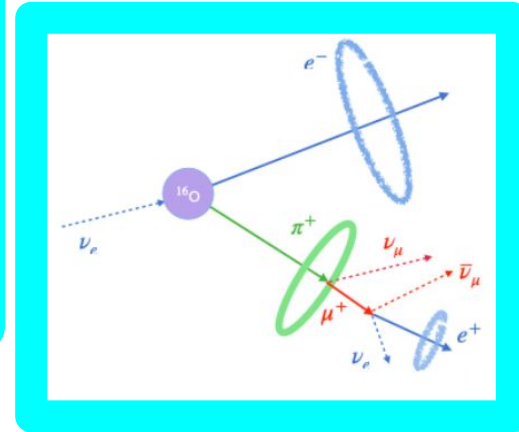
Reconstructed Neutrino Energy [MeV]

T2K Preliminary

$\bar{\nu}$ -beam: 1R μ

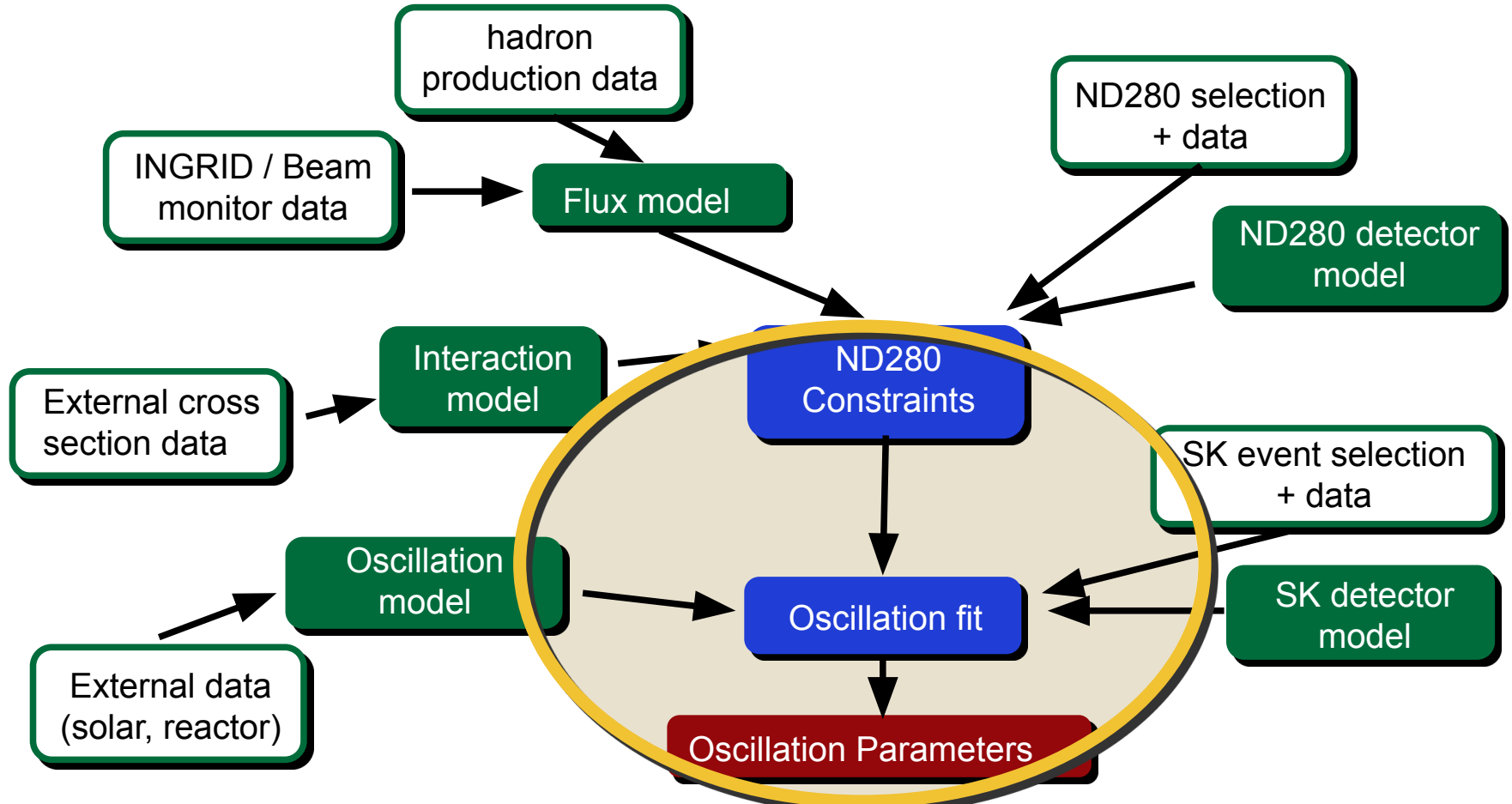


Reconstructed Neutrino Energy [MeV]



- New multi-ring contribution to ν_e CC 1 π sample

Oscillation Analysis

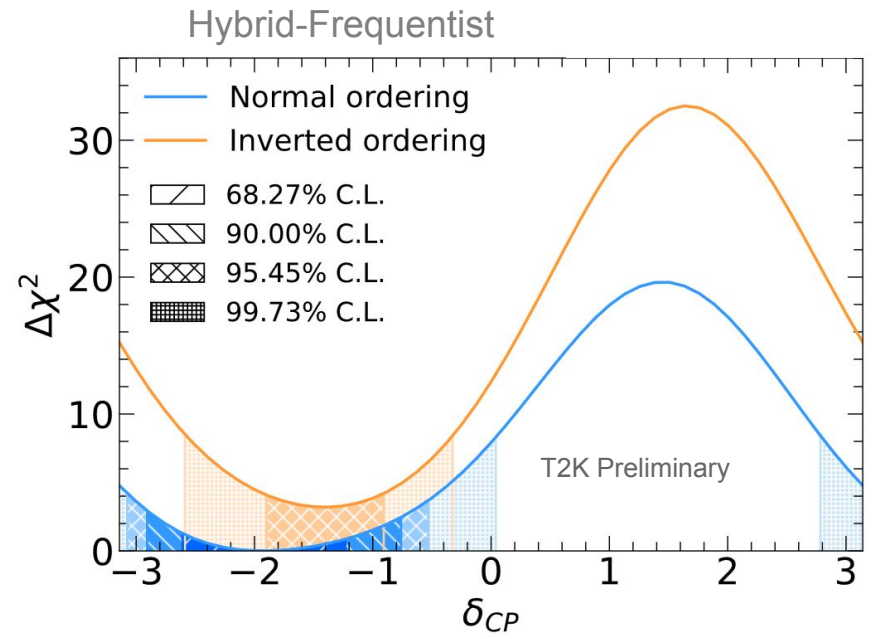


Preference for maximally CP-violating values CP-conservation excluded at the 95% C.L.

To test the **robustness** of our result:

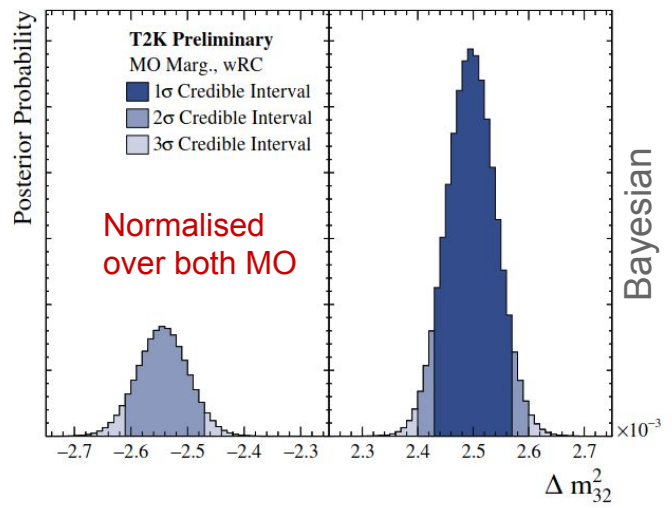
- 5 alternate cross-section models
- Compared with the nominal analysis.

→ CP Conservation is excluded at **95% CL**
for each of these tests.



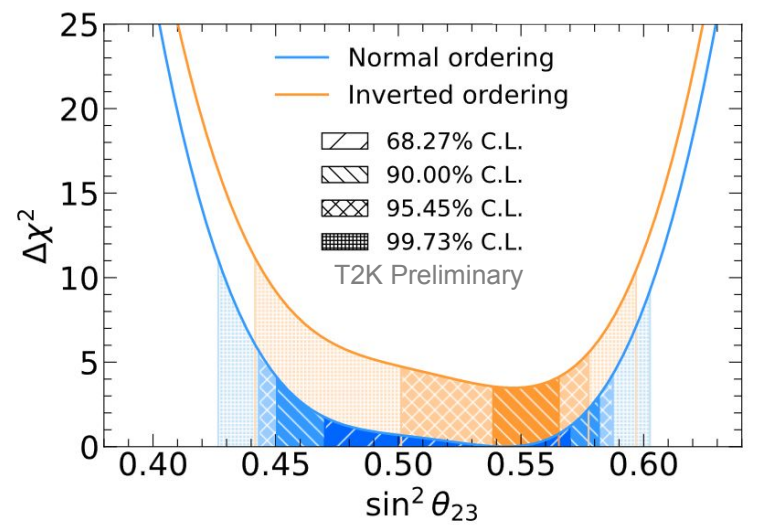
- Oscillation analysis performed independently with Bayesian and Hybrid-Frequentist frameworks
- Gaussian priors on Δm^2_{21} and $\sin^2\theta_{12}$ taken from PDG values [2025]
- Prior on θ_{13} using the reactor constraint (RC) is applied in the following plots
- Inflated uncertainty on Δm^2_{32} [NO] / $|\Delta m^2_{31}|$ [IO] - driven by alternate interaction model studies

T2K Oscillation Results



	$\sin^2 \theta_{23} < 0.5$	$\sin^2 \theta_{23} > 0.5$	Sum
NO ($\Delta m_{32}^2 > 0$)	0.271	0.509	0.780
IO ($\Delta m_{32}^2 < 0$)	0.061	0.159	0.220
Sum	0.332	0.668	1.000

- Weak preference for NO at 78% posterior probability
→ Increases to 81% when including Δm_{32}^2 data in the reactor constraint
- 1.9% total error on Δm_{32}^2 for fixed MO

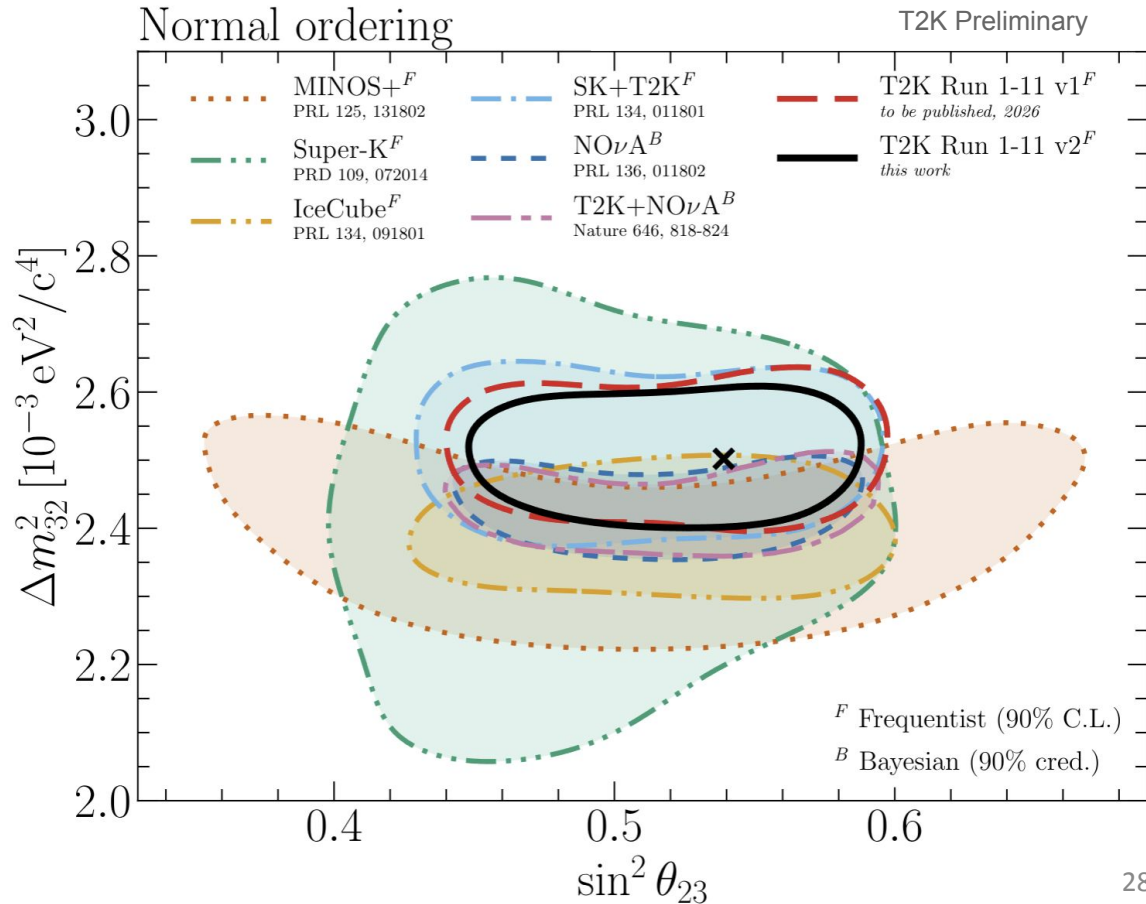


- IO ordering rejected at 93% C.L.
- Weak preference for upper octant, but a shift towards maximal mixing compared to previous analysis.
- Consistent with both octants at 68% C.L.

- The biggest improvement in the latest T2K result is due to the improved interaction model
 → Model bias driven error inflation on Δm_{32}^2 is reduced by a factor of 0.7
- Cross-section model related errors still dominate the total systematics error
- Previous analysis methodology
<https://arxiv.org/pdf/2606.14015>
 → ND280 upgrade is designed to improved these model further

Poster 1/#459

T. Schefke: T2K Oscillation Analysis



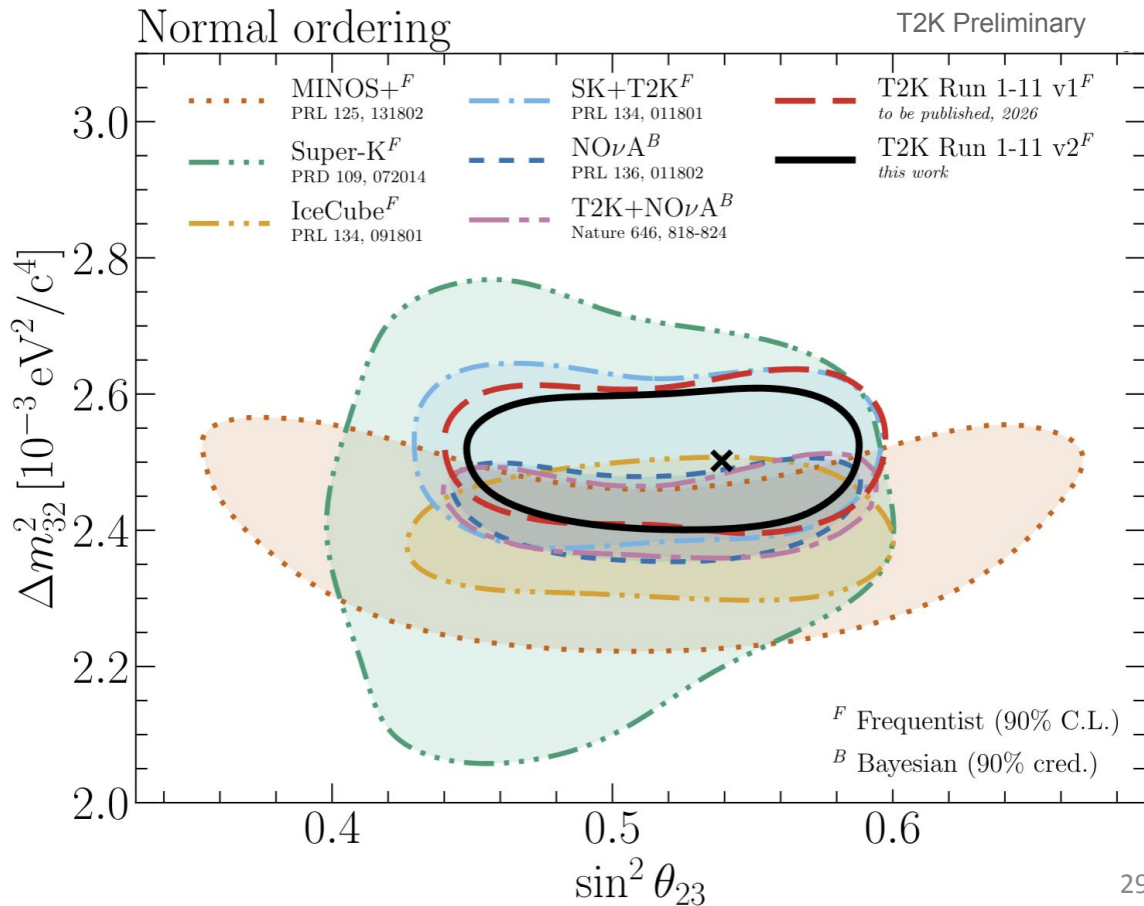
Joint analyses:

Combine inputs from experiments that have differing and complementary properties

→ Perform a joint fit to help break degeneracies

Updated analyses with NOvA and SK underway, including investigating potential to test effects of non-standard interaction

[Poster 2/#420](#)
[Poster 1/#499](#)
T2K-NOvA





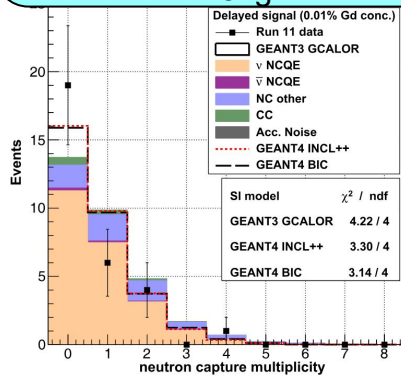
Other T2K Highlights

Neutron capture from NCQE with Gd data:

[P.R.D. 112.032003](#)

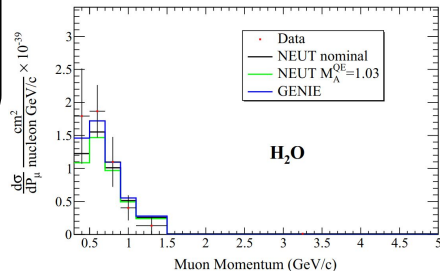
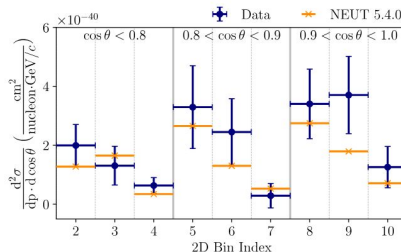
[Poster 1/#502](#)

- L. Feng -



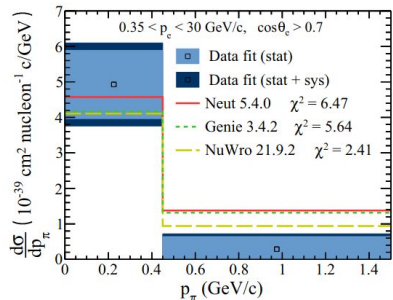
ND280 NC1 π^+

[P.R.D. 112.072008](#) [P.R.L. 135.171803](#)



WAGASCI-babyMIND

ν_μ CC 0 π [P.R.D. 112.112020](#)



ND280 ν_e CC π^+

[P.R.L. 135.151802](#)

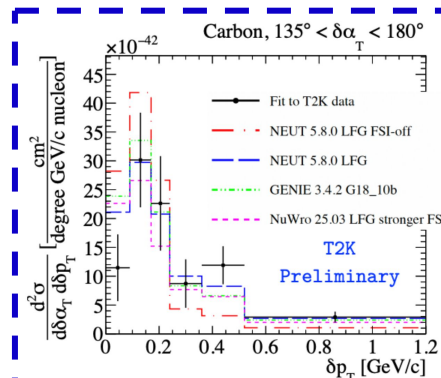
Coming Soon!

[Poster 2/#286](#)

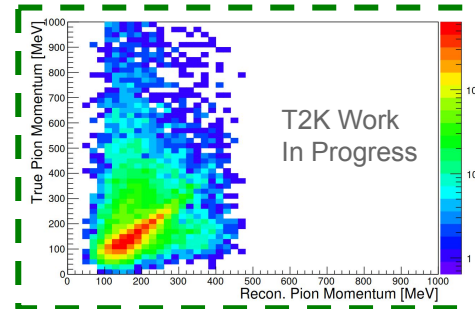
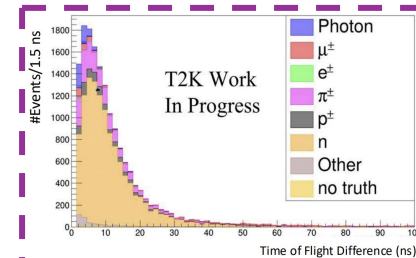
- N. Babu -

ND280 ν_μ CC 0 π on C and O

ν_μ CC 1 π on Water
Plot: Reconstructed momentum from pion decay delayed signal



ν_μ CC 0 π Np Transverse kinematic imbalance variables



ECal-based neutron tagging



ND280 Upgrade



ND280 Upgrade

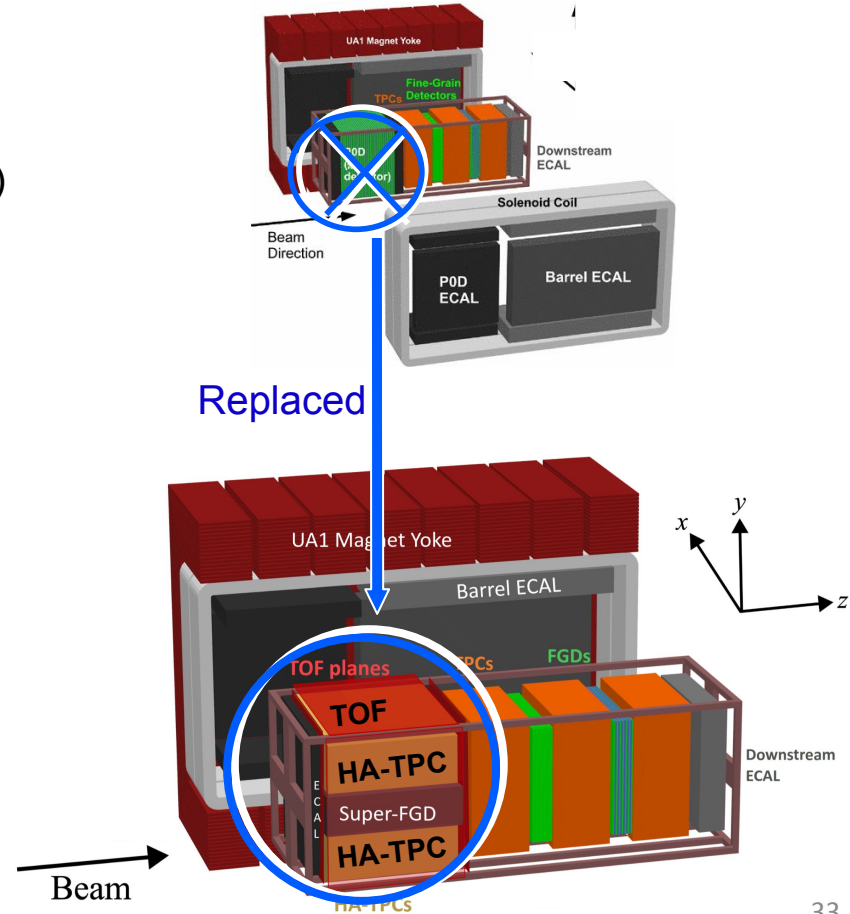
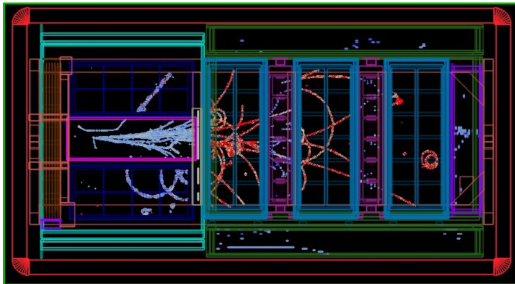
Goal: Precision tests of interaction models:

- Improved angular acceptance
- Reduce proton momentum threshold (~ 300 MeV/c)
- Neutron tagging and kinematics
- Increased target mass for greater statistics (FGD + SFGD)

Part of the P0D detector replaced with:

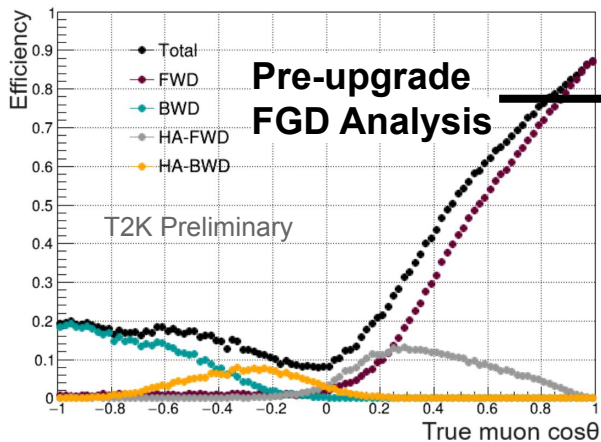
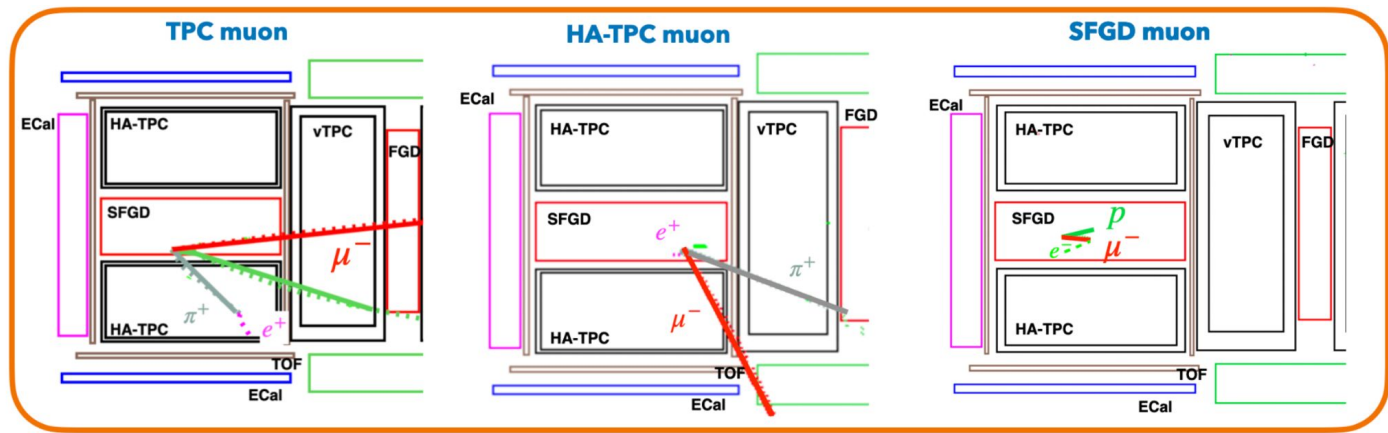
- New scintillator target: **SuperFGD (SFGD)**
- Two High-Angle TPCs: **HA-TPC**
- 6 Time of Flight planes: **TOF**

Installation
completed
in May 2024



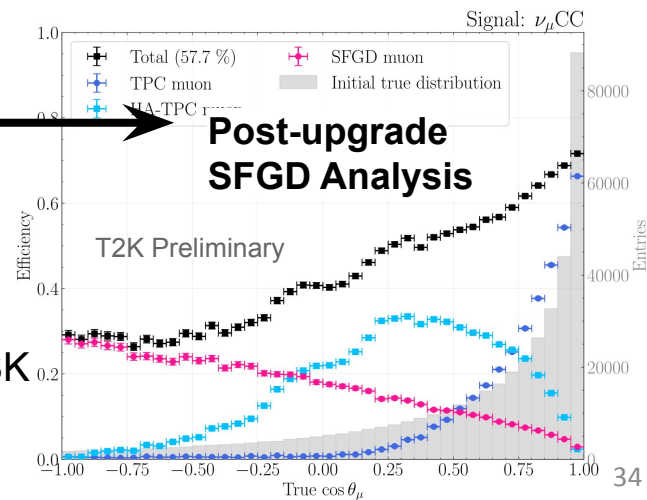
ν_μ CC Inclusive Event Selection

- SFGD as target
- ν_μ CC events selected according to muon sub-detector trajectory



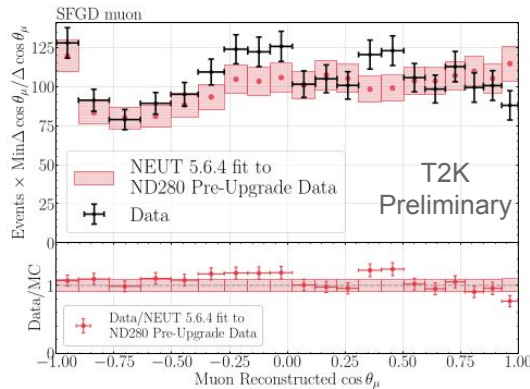
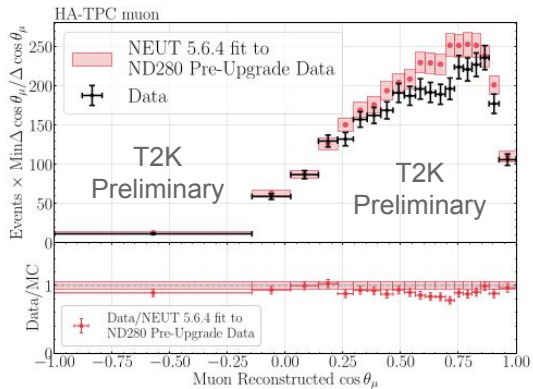
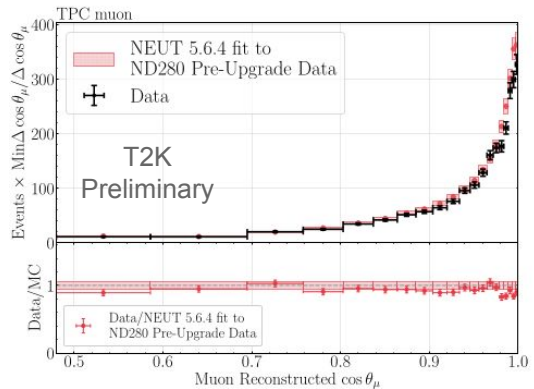
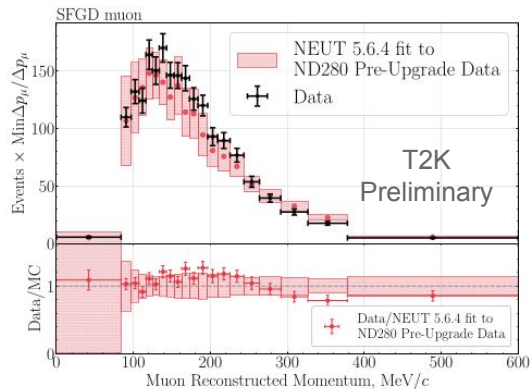
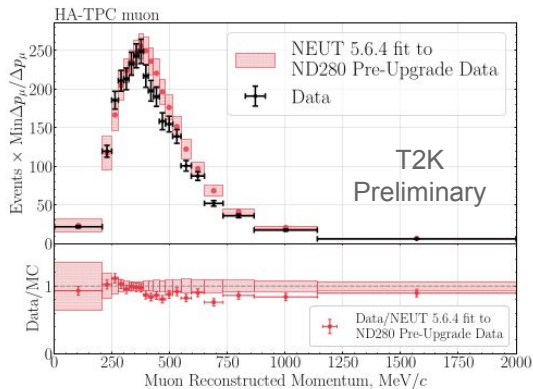
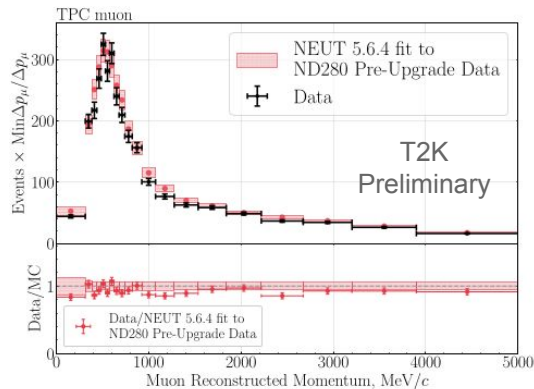
Configuration of new detectors improves angular acceptance

→ Important for extrapolation to SK



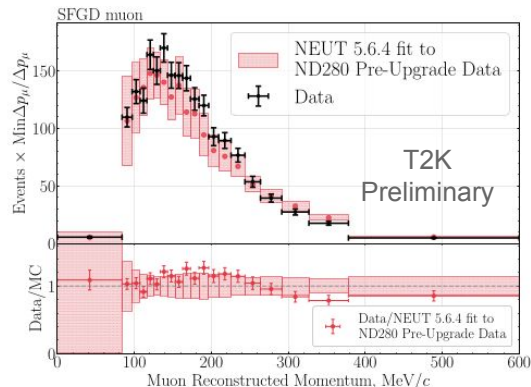
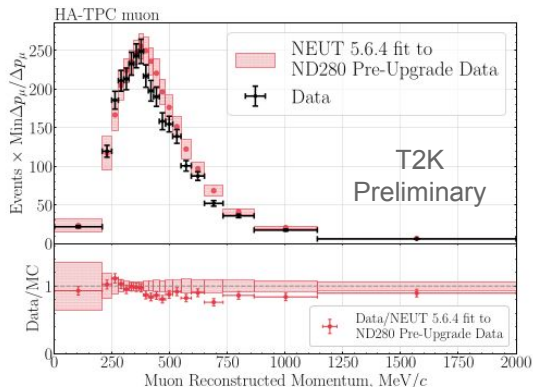
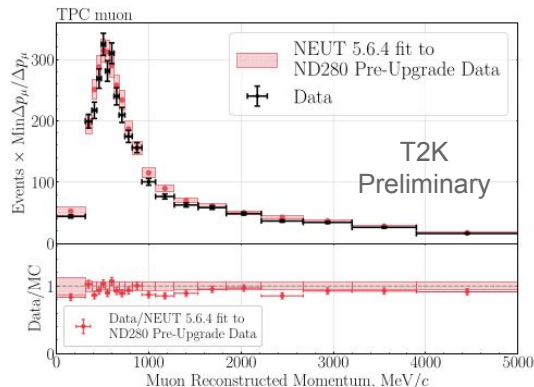
ν_μ CC Inclusive Event Selection

- Reconstructed distributions with MC tuned to pre-upgrade best fit value
- Statistical and (Flux + Detector) systematic error band on MC



ν_{μ} CC Inclusive Event Selection

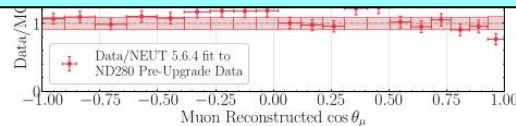
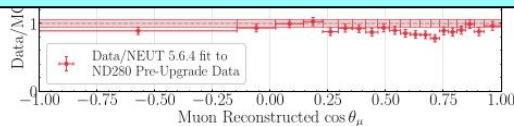
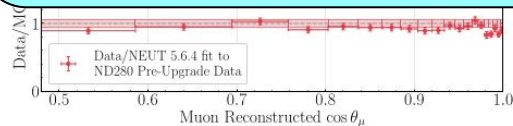
- Reconstructed distributions with MC tuned to pre-upgrade best fit value
- Statistical and (Flux + Detector) systematic error band on MC



ν_{μ} CC event selection finalised, with full set of detector systematics computed

→ Validates detector model for ND280 upgrade

→ Forms the basis for exclusive event selections based on final state particle combinations



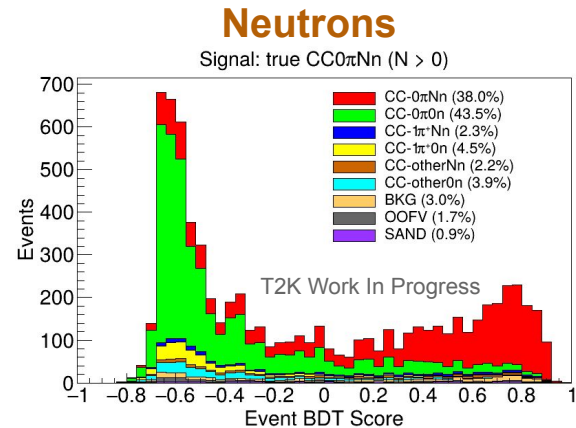
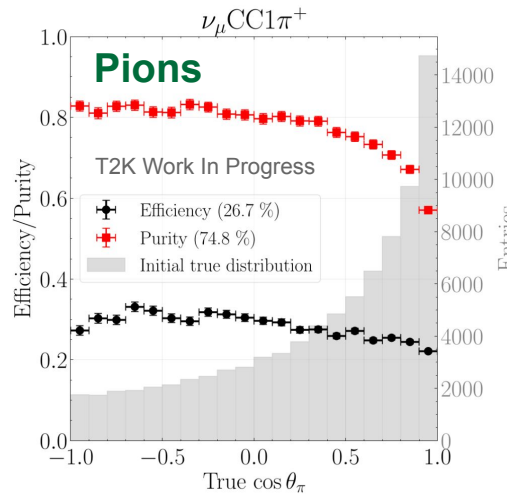
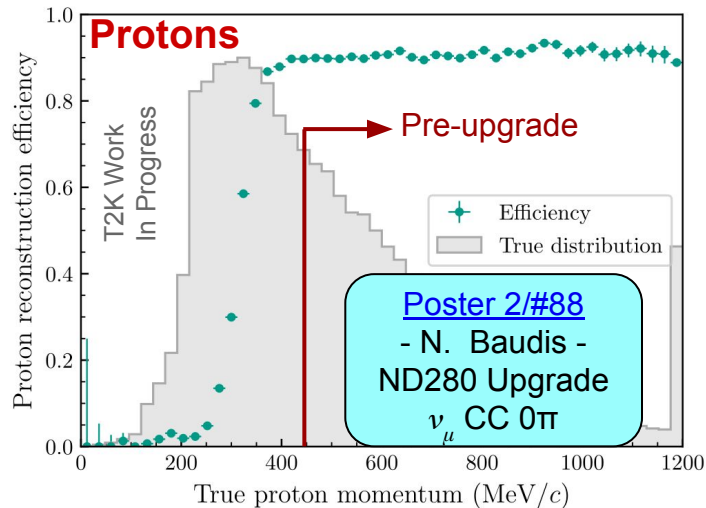
ND280 Upgrade Exclusive Interactions

Nuclear effects in neutrino-nucleus interactions affect final state particle topology and kinematics

- Bias neutrino **energy reconstruction**
- Associated uncertainties will limit future **sensitivity to CP-violation**

→ **ND280 upgrade will constrain interaction models for future oscillation measurements**

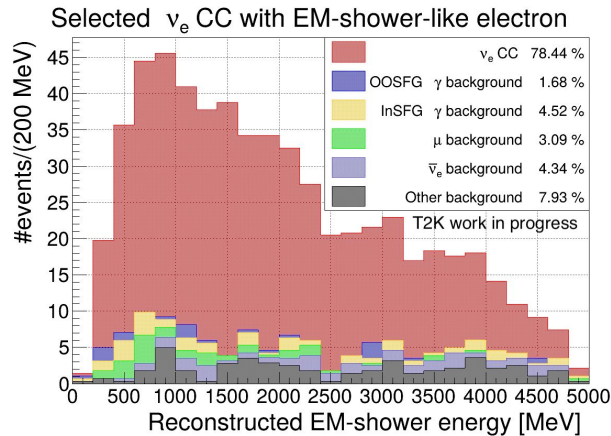
- Reconstruct **protons, pions, neutrons** to study different interaction topology combinations
- **Projections** (e.g. Transverse Kinematics Imbalance Variables, Adlers Angle etc.)
- probe **nuclear and nucleon** effects, **pion production** models, **2p2h, FSI** etc



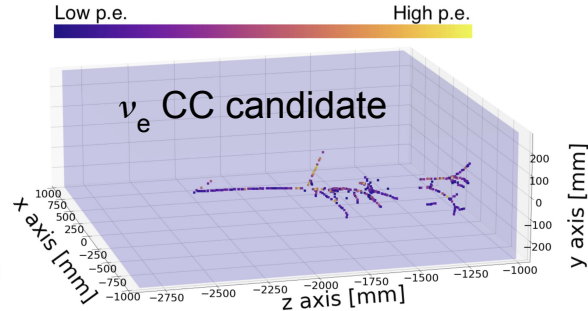
ND280 Upgrade Exclusive Interactions

ν_e CC

- ν_e : Oscillation appearance signal at the far detector
Need to understand intrinsic ν_e component to the beam
→ ND280 can constrain this!



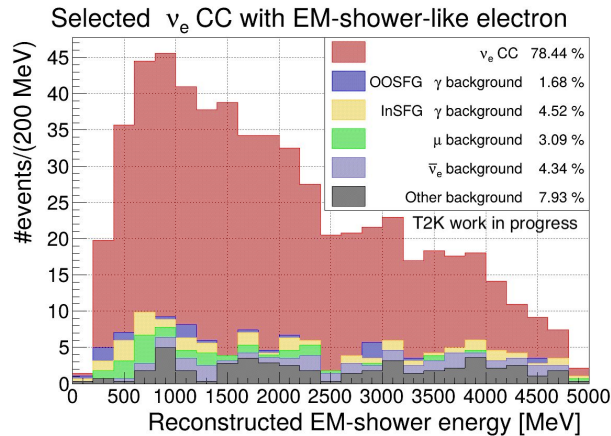
- Compared to pre-upgrade: - **Reduced** electron **energy threshold**
- **Reduced** in **photon background**



[Poster 1/#109](#)
- H. Kobayashi -
ND280 upgrade ν_e CC

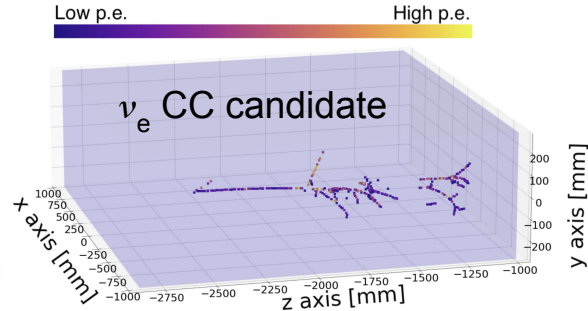
ND280 Upgrade Exclusive Interactions

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[Poster 1/#109](#)
- H. Kobayashi -
ND280 upgrade ν_e CC

Outlook

Coming soon: MC-data model comparisons in reconstructed variables and projections

In the pipeline: Integration into T2K oscillation analysis, and work towards cross-section extraction



Beam Upgrades

Beamline-Upgrade (2021/2022)

- Upgraded main ring power supplies: Repetition rate reduced: 2.48 \rightarrow 1.28 s
- Electromagnetic Horn system upgrade: Current increased 250 \rightarrow 320 kA
 \rightarrow Flux increased by $\sim 10\%$ and wrong-sign background reduced 5-10%
- Beam power of **900kW!**

Further upgrades:

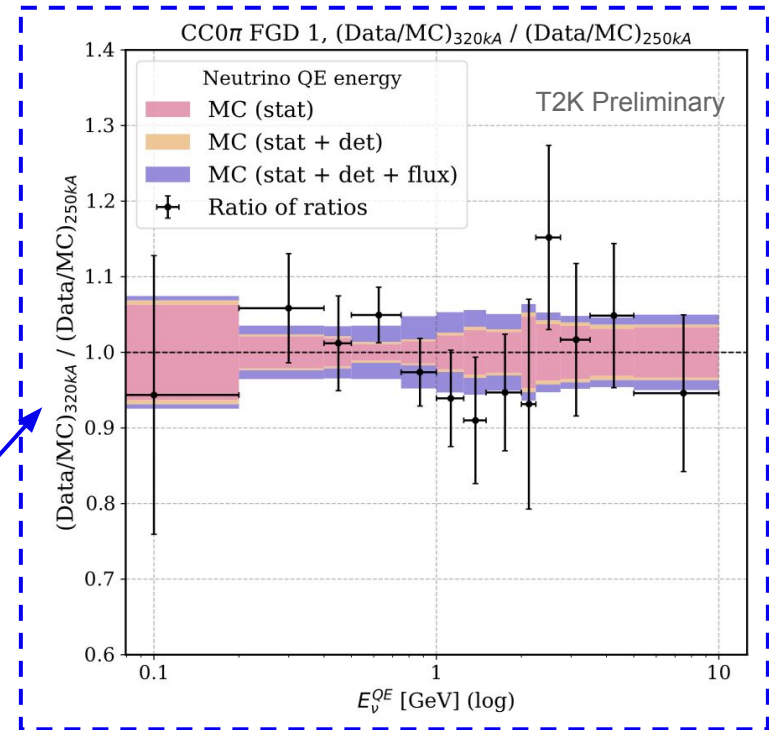
- Reduce repetition rate to 1.16 s
- Reach a beam power of **1.3 MW**

[Poster 1/#47](#)
- A. Asai -
Beam target
protection system

ND280 validated the flux simulation
after the beam upgrade

(Data/MC) 320kA

(Data/MC) 250kA

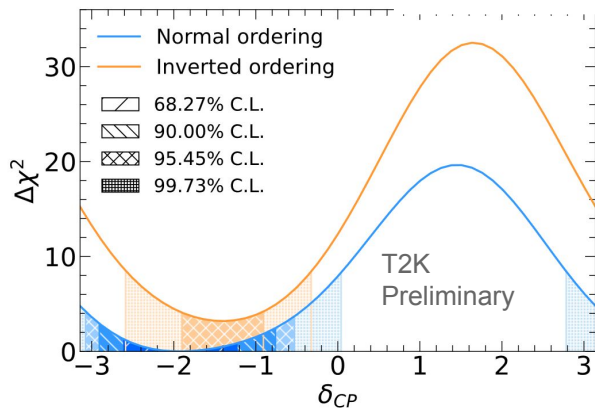




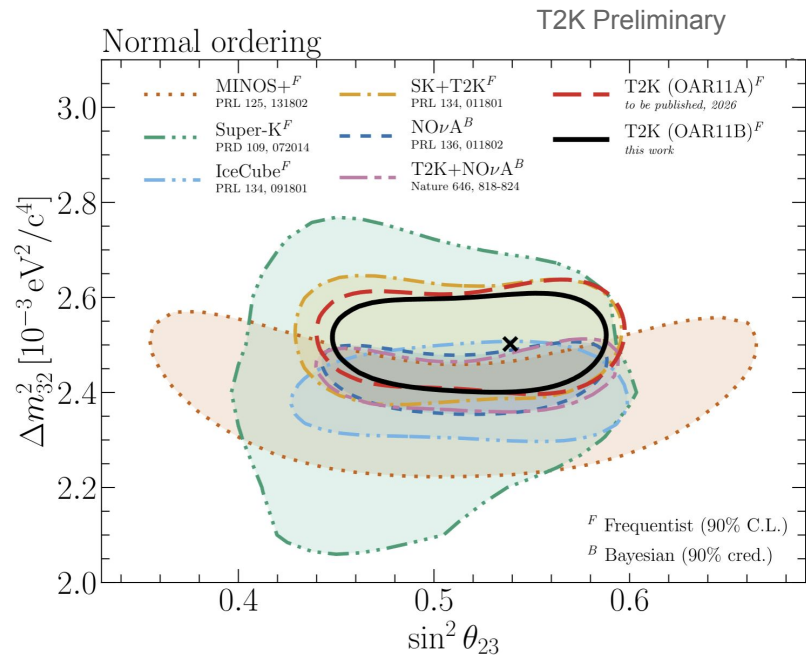
Summary

T2K provides competitive constraints on δ_{CP} , Δm_{32}^2 , θ_{13} and θ_{23}

- T2K excludes CP-conservation at the 95% CL, with a weak preference for NO and θ_{23} upper octant
- Continued collaboration between T2K & SK and T2K & NOvA



	$\sin^2 \theta_{23} < 0.5$	$\sin^2 \theta_{23} > 0.5$	Sum
NO ($\Delta m_{32}^2 > 0$)	0.271	0.509	0.780
IO ($\Delta m_{32}^2 < 0$)	0.061	0.159	0.220
Sum	0.332	0.668	1.000



T2K provides competitive constraints on δ_{cp} , Δm^2_{32} , θ_{13} and θ_{23}

- T2K excludes CP-conservation at the 95% CL, with a weak preference for NO and θ_{23} upper octant
- Continued collaboration between T2K & SK and T2K & NOvA

Testing and constraining systematics for future oscillation measurements

- Cross-section model errors still dominate the total systematic error
 - Many recent [cross-section publications](#) from T2K, and more results on the way
 - [ND280 upgrade](#) designed to test and constrain these models

Stay tuned for new results

- [New data](#) from SK, and the first [physics publications from the ND280 upgrade](#) are coming soon



BACKUP



Oscillation Analysis Backup

Frequentist framework

Without reactor constraint

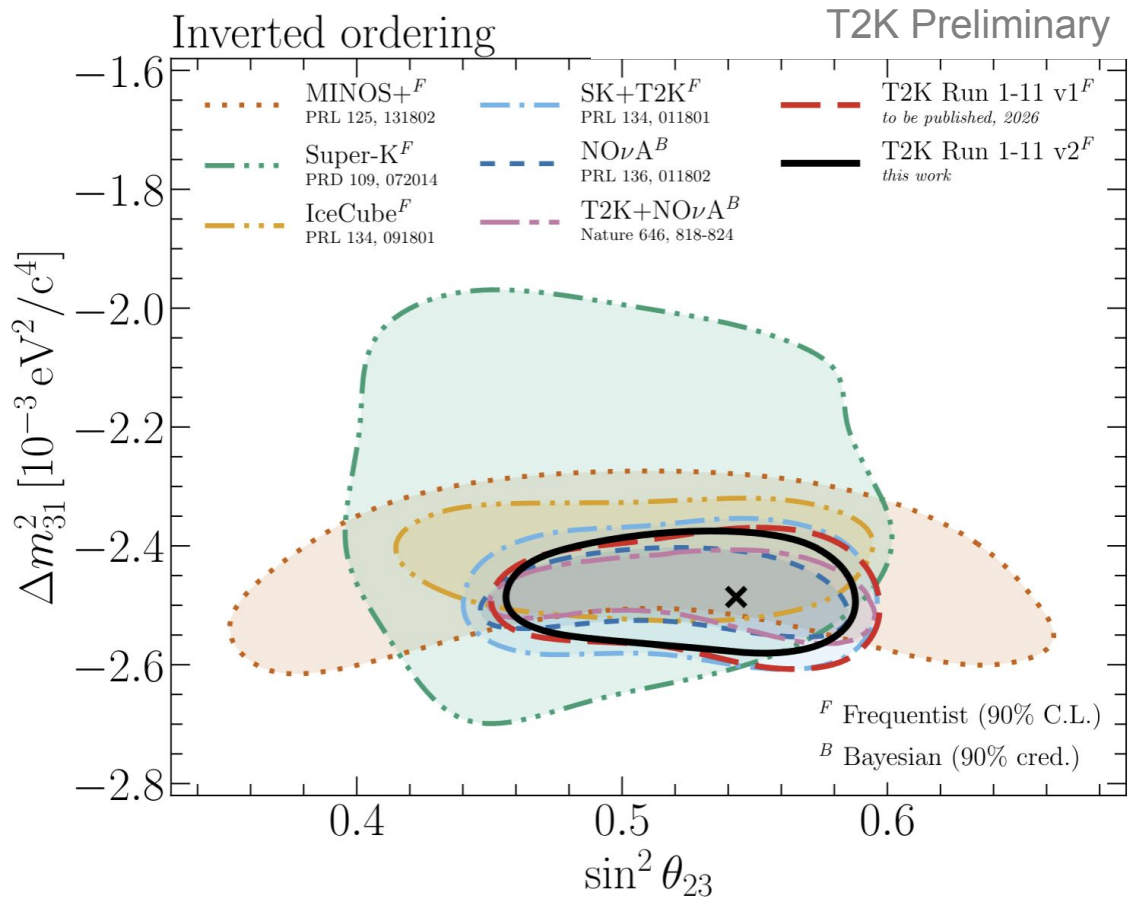
	Normal ordering	Inverted ordering
$\sin^2 \theta_{13}$ [10^{-3}]	$25.2^{+3.7}_{-4.3}$	$28.0^{+3.3}_{-4.8}$
δ_{CP} [rad]	$-2.18^{+0.77}_{-0.73}$	$-1.25^{+0.60}_{-0.65}$
Δm_{32}^2 [10^{-3} eV 2]	$2.503^{+0.053}_{-0.046}$	–
Δm_{31}^2 [10^{-3} eV 2]	–	$-2.471^{+0.054}_{-0.041}$
$\sin^2 \theta_{23}$	$0.486^{+0.074}_{-0.027}$	$0.485^{+0.077}_{-0.027}$
$-2 \ln \mathcal{L}$	589.604	591.145
$-2 \Delta \ln \mathcal{L}$	0.	1.5410

With reactor constraint

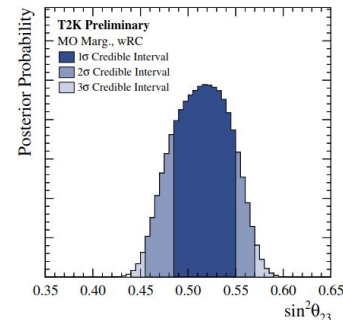
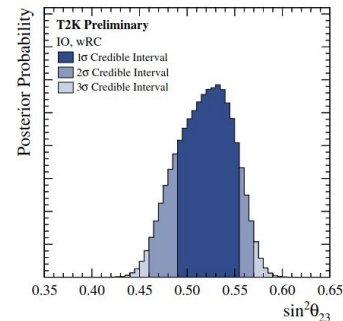
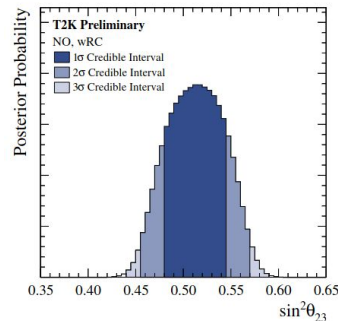
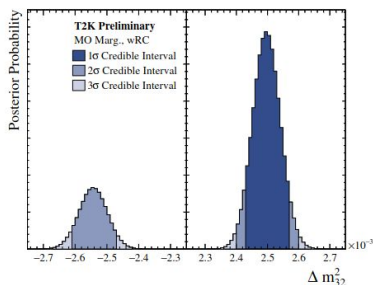
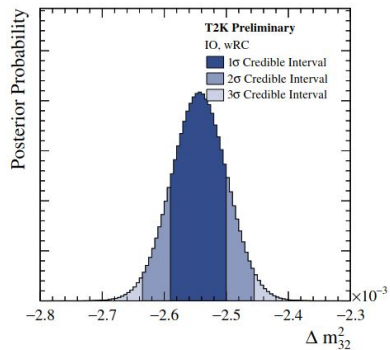
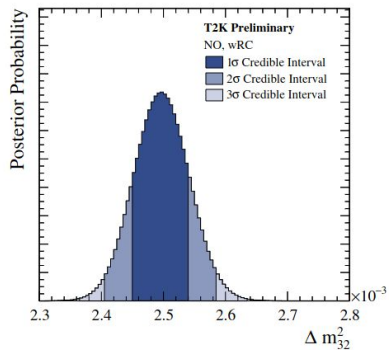
	Normal ordering	Inverted ordering
$\sin^2 \theta_{13}$ [10^{-3}]	$21.6^{+0.7}_{-0.6}$	$21.6^{+0.7}_{-0.5}$
δ_{CP} [rad]	$-2.04^{+0.81}_{-0.56}$	$-1.37^{+0.58}_{-0.69}$
Δm_{32}^2 [10^{-3} eV 2]	$2.502^{+0.052}_{-0.044}$	–
Δm_{31}^2 [10^{-3} eV 2]	–	$-2.486^{+0.058}_{-0.037}$
$\sin^2 \theta_{23}$	$0.539^{+0.031}_{-0.069}$	$0.543^{+0.036}_{-0.058}$
$-2 \ln \mathcal{L}$	589.904	592.748
$-2 \Delta \ln \mathcal{L}$	0.	2.844

In both cases, the best global fit is in NO

T2K Oscillation Analysis



T2K Oscillation Analysis: Bayesian

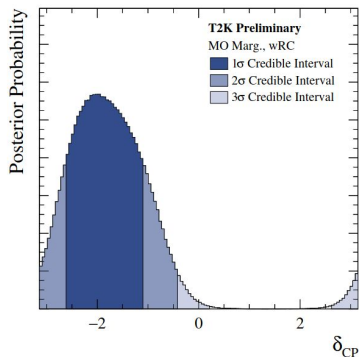
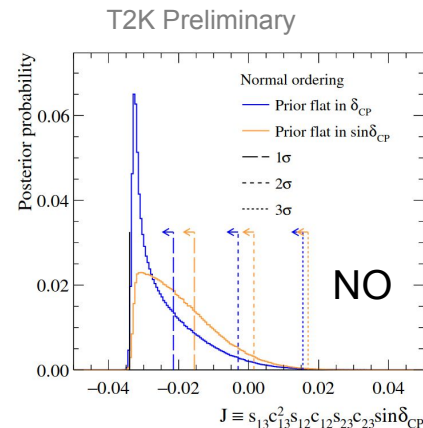
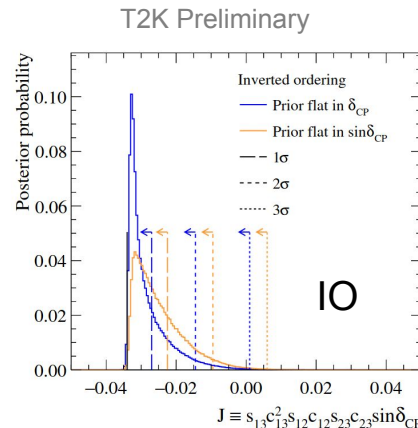
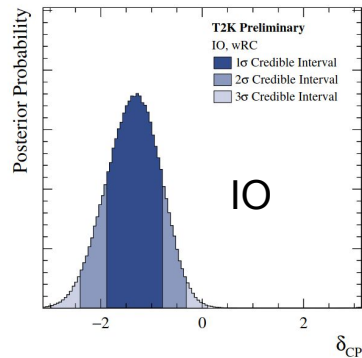
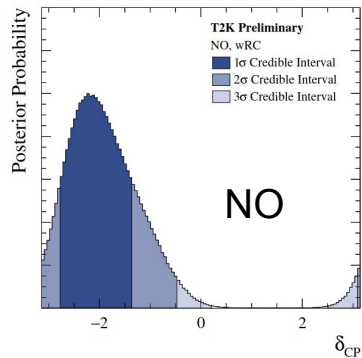


Weak preference for normal ordering (NO) at 78% posterior probability

	$\sin^2 \theta_{23} < 0.5$	$\sin^2 \theta_{23} > 0.5$	Sum
NO ($\Delta m_{32}^2 > 0$)	0.271	0.509	0.780
IO ($\Delta m_{32}^2 < 0$)	0.061	0.159	0.220
Sum	0.332	0.668	1.000

Weak preference for upper octant at 67% posterior probability

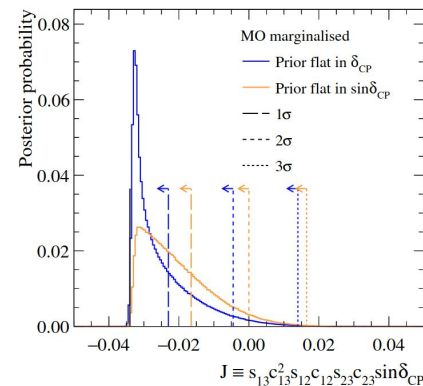
T2K Oscillation Analysis: Bayesian

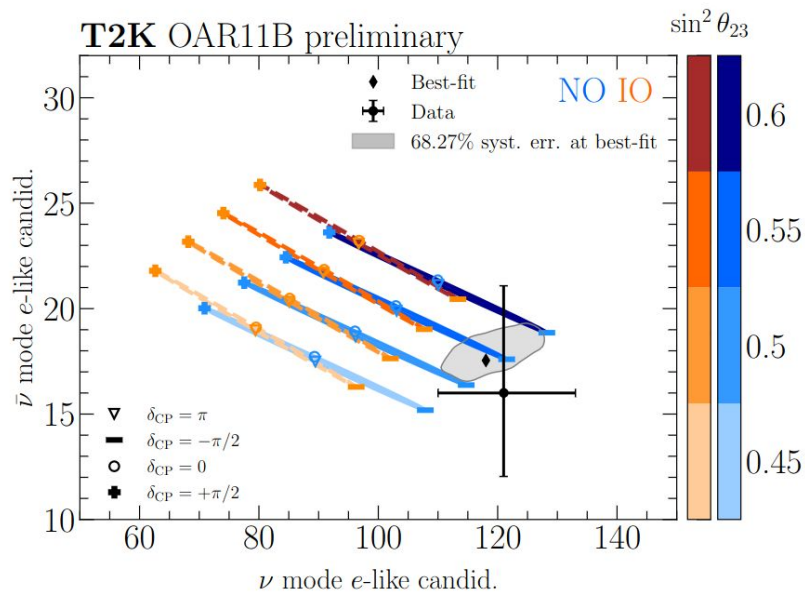


Bayesian significance:

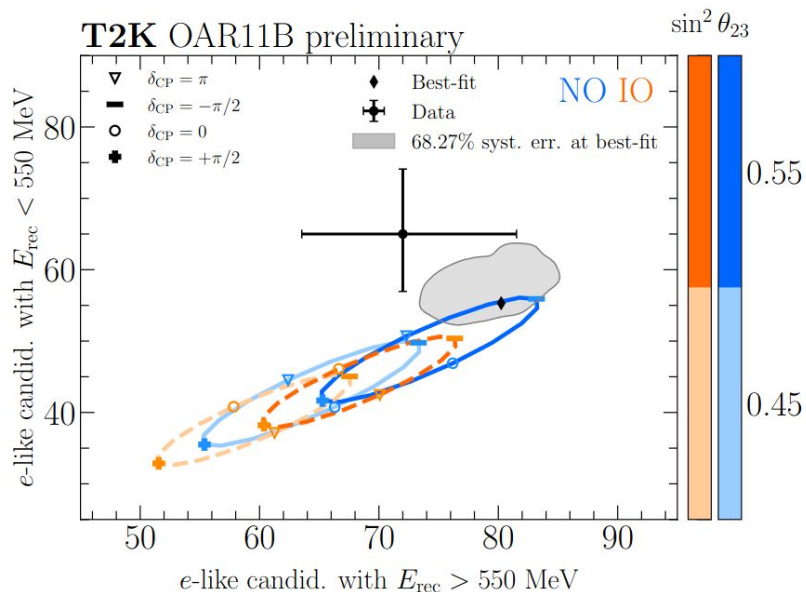
Longest credible interval not containing the CP-conserving value of the Jarlskog invariant

- 97% (flat δ_{CP} prior)
- 95% (flat $\sin\delta_{CP}$ prior)





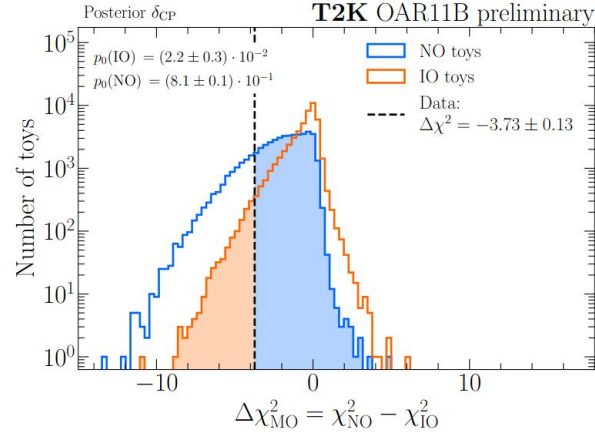
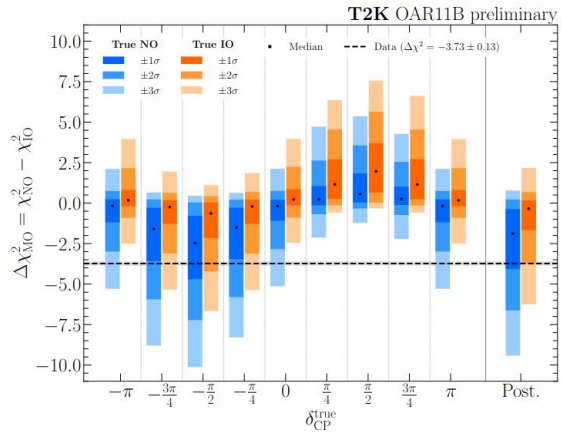
FHC Vs RHC: e -like candidates



$E > 500$ MeV Vs $E < 500$ MeV:
(FHC+RHC) e -like candidates

Frequentist analysis

	p -value	Z -score
Inverted ordering	$(2.2 \pm 0.3) \times 10^{-2}$	2.01 ± 0.06
Normal ordering	$(8.1 \pm 0.1) \times 10^{-1}$	-0.86 ± 0.05



NO preferred, but highly dependent on value of δ_{cp}

- Frequentist analysis: $(2.01 \pm 0.06) \sigma$ rejection of IO

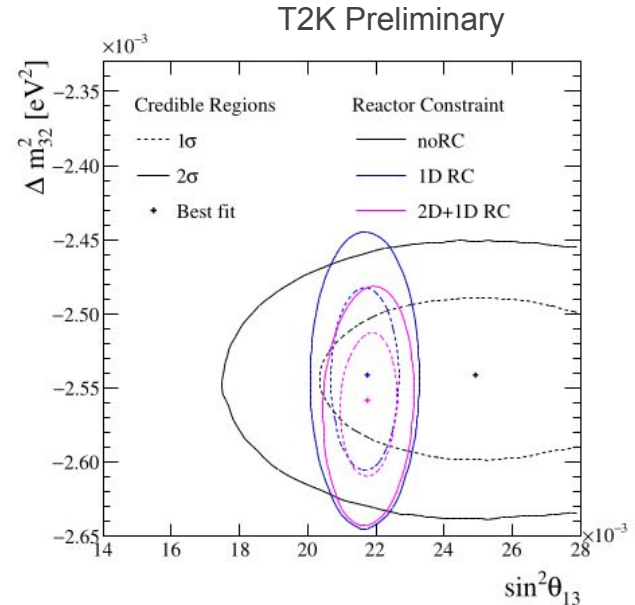
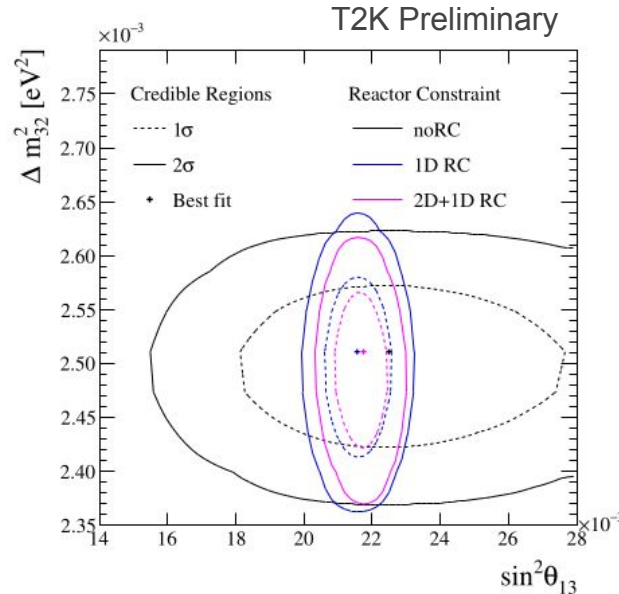
Including reactor Δm_{32}^2 information

1D reactor constraint: $\sin^2\theta_{13}$. T2K results presented with the 'reactor constraint (RC)' refer to this.

2D reactor constraint: 1D constraint plus information on the relationship between Δm_{32}^2 and $\sin^2\theta_{13}$ provided by the $\Delta\chi^2$ surfaces published by Daya Bay and RENO

Including the 2D constraint increases the preference for NO (78 \rightarrow 81% posterior probability)

Greater disagreement between the highest posterior density points in the case of IO



SK Event Selection Error Sources

Error source	FHC 1R		RHC 1R		FHC MR		Ratio e -like FHC/RHC
	e -like	μ -like	e -like	μ -like	ν_e CC1 π	ν_μ CC1 π	
<i>SK detector uncertainties</i>							
SI+PN [⊕]	0.6	0.4	1.0	0.3	2.3	2.0	0.5
Energy scale [⊕]	0.3	0.7	0.9	0.1	0.5	0.1	1.0
Det. syst. [⊕]	1.5	0.7	2.3	0.7	2.7	2.7	0.9
SK (all)	1.6	1.1	2.7	0.8	3.6	3.3	1.4
<i>Flux and cross-section (ND constrained)</i>							
Flux	2.9	2.9	3.0	2.9	2.9	2.9	2.4
Xsec (ND constr.)	5.2	4.5	4.6	4.3	3.9	3.2	3.4
Flux+Xsec (ND constr.) [⊕]	4.3	3.6	3.9	3.5	3.1	2.2	3.5
<i>Cross-section (ND unconstrained)</i>							
SF MF p_{miss} shape [⊕]	0.3	0.3	0.2	0.2	0.0	0.0	0.1
2p2h E_ν -dependent [⊕]	0.1	0.2	0.1	0.2	0.0	0.0	0.1
$I = 1/2$ non-res. bkg. $\bar{\nu}$ low- p_π [⊕]	0.1	0.4	2.3	2.7	0.1	0.9	2.1
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$ [⊕]	3.2	0.0	1.7	0.0	2.7	0.0	2.7
NC coherent norm. [⊕]	0.1	0.0	0.3	0.0	0.0	0.0	0.3
NC 1 γ norm. [⊕]	0.6	0.0	0.9	0.0	0.0	0.0	0.3
NC other (far) [⊕]	0.1	0.2	0.3	0.2	2.1	1.0	0.1
Xsec (ND unconstr.)	3.3	0.5	3.1	2.7	3.4	1.4	3.5
<i>Flux and cross-section (all)</i>							
Flux+Xsec (all)	5.4	3.7	4.9	4.3	4.7	2.6	4.9
Total[†]	5.7	3.7	5.7	4.4	5.9	4.2	5.1

[†]Quadrature sum of the groups of parameters marked [⊕], which are mutually uncorrelated.

Framework 1: Hybrid-Frequentist

- Two stages:
 - ND280 data fit
→ New fitting framework
 - SK data fit, using ND280 constraints
- Frequentist methods using marginal likelihood.
- Feldman-Cousins method used to obtain confidence levels

Framework 2: Bayesian

- Simultaneously fit:
 - A single fit uses both ND280 and SK inputs to constrain the oscillation parameters.
- Bayesian methods using Markov Chain Monte Carlo.
- Credible intervals obtained from the posterior distributions.

Oscillation Parameters

Improvements since Neutrino 2024

(T2K Run 1-11 v1 → T2K Run 1-11 v2)

- New low energy transfer dials describing the strength of Continuum-Random Phase Approximation (CRPA) and FSI
- Removal of Pauli Blocking for CCQE and RES at production time, and new 1π Pauli Blocking dials.
- New Short Range Correlations uncertainty added to the Spectral Function CCQE channel
- Improved 2p2h implementation
- Nucleon FSI cascade reweighting (equivalent to pion FSI) replaces fate-based reweighting
- New Bodek-Yang effective uncertainty for NC DIS/Mpi
- Updated ν_e/ν_μ uncertainty
- A correction to the total cross section derived from the colinear part of the radiative correction calculation

- Good agreement between both fitter frameworks in general
- Most parameters agree with pre-fit values

Det sys

- Noticeable for weighted detectors systematics
 - Proton and Pion secondary interaction
 - Error is strongly constrained
 - Some param pulled outside 1 or 2 sigma ranges
 - ECal tracking eff and TPC-ECal matching noticeably adjusted
- Sensitivity predicted in asimov fit
- Variation detector systematics (cov matrix)
 - Show good agreement between both fitter frameworks

Flux

- Post-fit predicts higher flux (up to 10%) across most energy bins, and lower flux in highest energy bin
- Post-fit generally compatible with pre-fit
- Similar trend to previous analyses
- Show good agreement between both fitters

Cross-section model

- Postfit values from both fitter frameworks are compatible
- Postfit errors from both fitters are compatible, but differences are noticed for RPA, FSI and 2p2h shape, due to a differing interpolation method for these parameters between the fitters

- M_A^{QE} pulled up to 1.2 GeV (Similar to previous analysis)
- High Q^2 param are anti-correlated with M_A^{QE}
- SF norm params have expected anti-correction
- Higher Pauli blocking threshold predicted for Carbon
- Lower binding energies predicted
- New RPA and FSI param generally prefer a higher correction
- Anti-correlation between Pauli blocking and RPA-FSI strength (both affect low- Q^2 region)
- 2p2h norm reduced and correlated between nu and nubar (correlation not put into pre-fit)
- 2p2h shape param show anti-correlation with SRC norm for carbon (2p2h and SRC describe similar interactions)
- Pion production binding energy goes to 0 (same as previous analysis)
- Multi-pion total cross section is reduced
- Bodek-Yang axial param prefers a higher correction

Nuclear model for CCQE

1. Spectral Function (SF) to Local Fermi Gas (LFGC)
2. SF to Continuous Random Phase Approximation (CRPA)

CC0pi nonQE

3. ND280 data driven CC0pi nonQE
 - CCQE param have more freedom, need to make sure they are not absorbing non-QE effects

Pion production

4. 1 pion kinematics -3 sigma
5. 1 pion kinematics +3 sigma

SK atmospheric neutrino samples used as control samples to constrain the uncertainty on selection variables for neutrino beam events

→ Smear and bias/shift params extracted from MCMC fit to the atmospheric samples for each variable

Novelties in the Neutrino 2024 T2K analysis

- Updated to include single ↔ multi-ring sample migrations, allowing better correlations
- Systematic variations done directly from the MCMC posteriors instead of converting them to an intermediate covariance matrix → reduce overestimation of errors

Novelties in this analysis

- Inclusion of the new multi-ring ν_e CC 1π sample
- Updated visible energy binning in the atmospheric fit to focus on physics-motivated phase spaces
- Further improvements to single ↔ multi-ring sample migrations
- Updated xs model allows the removal of ad-hoc uncertainties
- Secondary interaction and photo-nuclear effects now have free parameters in the oscillation fit (previously they were added in the SK detector matrix before)

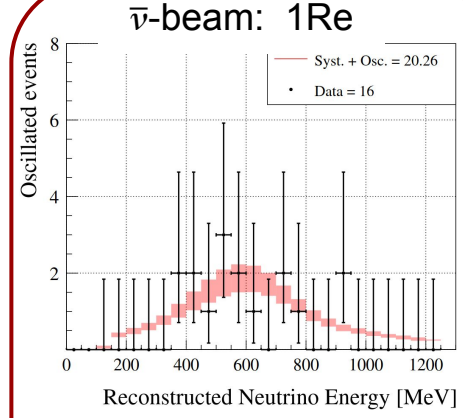
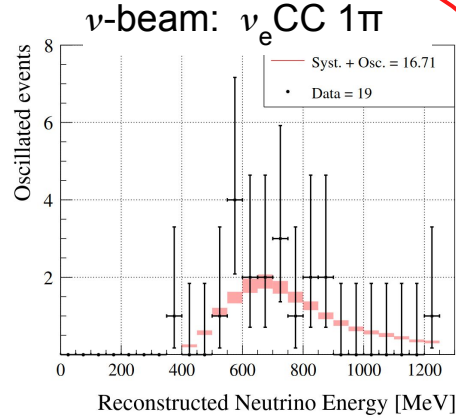
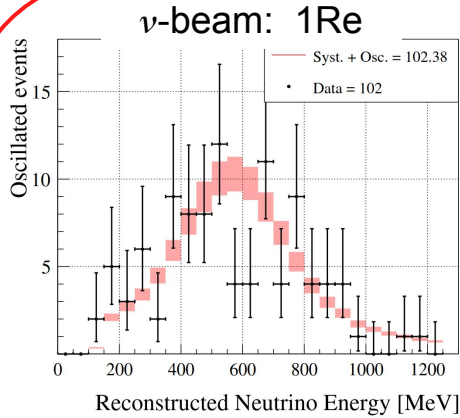
SK Event Samples

ν -mode

$\bar{\nu}$ -mode

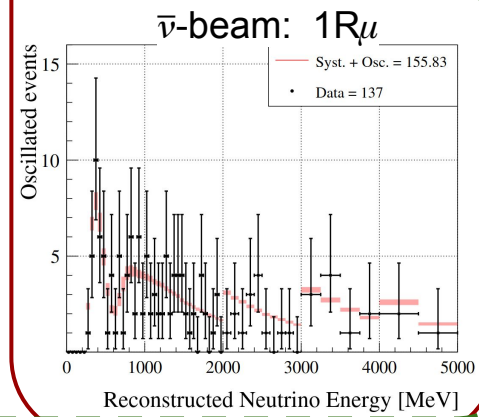
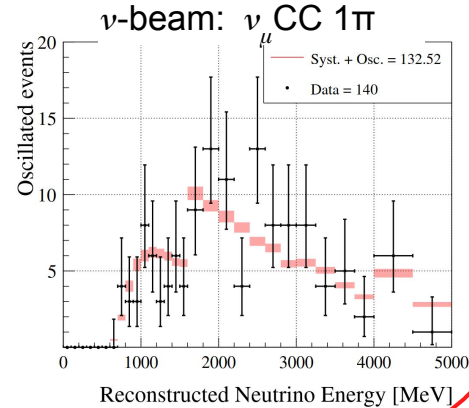
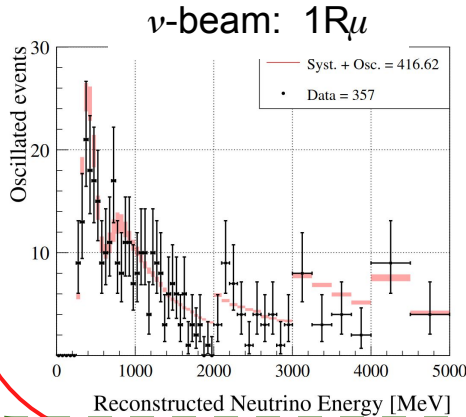
e-like

T2K Preliminary



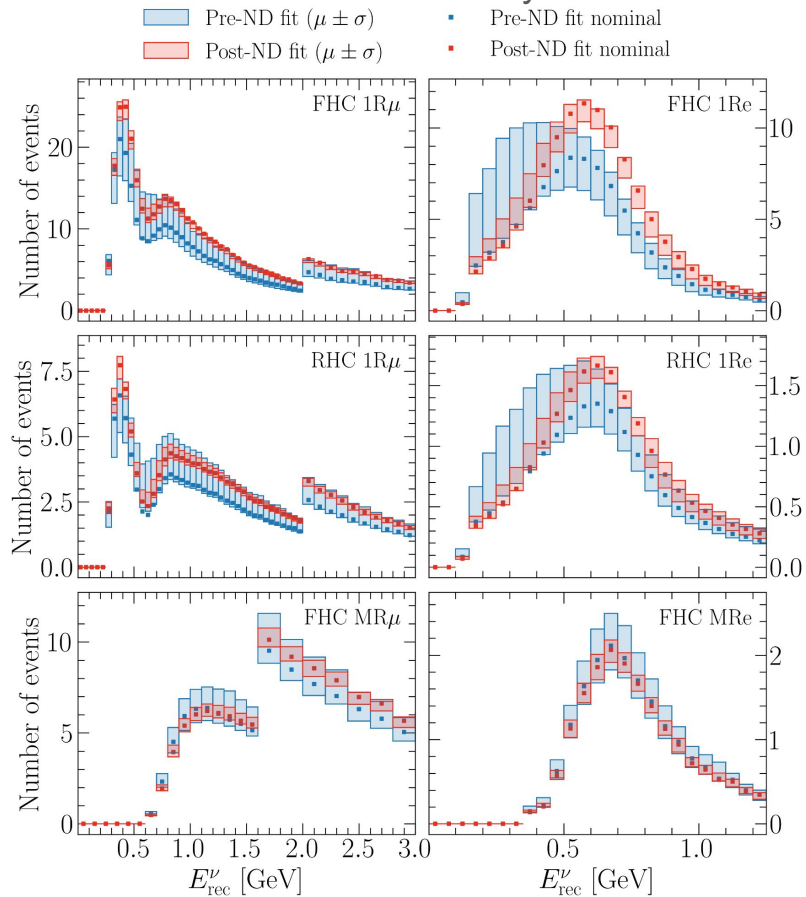
μ -like

T2K Preliminary



SK Event Samples with ND280 constraint

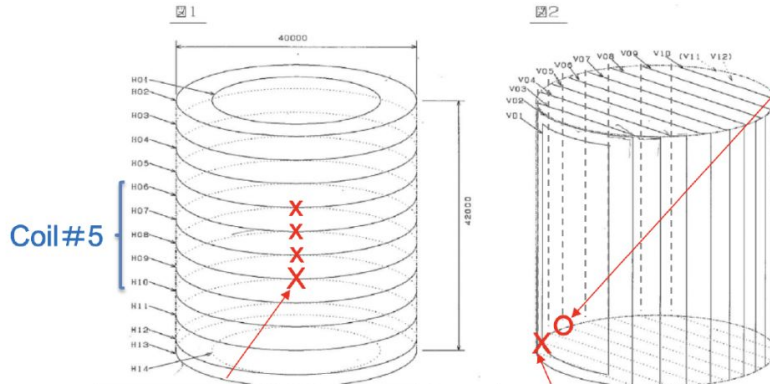
T2K Preliminary



SK event selection errors(%)

Pre fit \rightarrow post fit

FHC 1-Ring mu	19.2 % \rightarrow 3.7 %
FHC 1-Ring e	20.3 % \rightarrow 5.7 %
RHC 1-Ring mu	17.5 % \rightarrow 4.4 %
RHC 1-Ring e	20.3 % \rightarrow 5.7 %
FHC numuCC1pi+	12.3% \rightarrow 4.2 %
FHC nueCC1pi+	14.5% \rightarrow 5.9 %
FHC/RHC e	12.6 % \rightarrow 5.1%

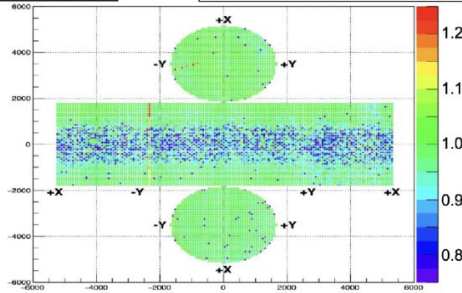


H09 disconnected on Dec.8, 2023.
Due to power supply configuration,
H06, H07, and H08 are also off.

V01 disconnected on Nov.15, 2023.
V01 was bypassed from the power
supply on Dec.2, 2023.

V06 disconnected on Oct.25, 2023.
Damaged sub-cable was bypassed on Dec.1, 2023. [recovered]

PMT photoelectron
collection efficiency ratio,
comparing May 2024
condition to nominal



SK geomagnetic compensation coils failed in 3 locations

~10-20% decrease in collection efficiency observed for ~20% of barrel PMTs

Likely cause was corrosion of wire connections due to ionized water seeping in under heat shrink insulation

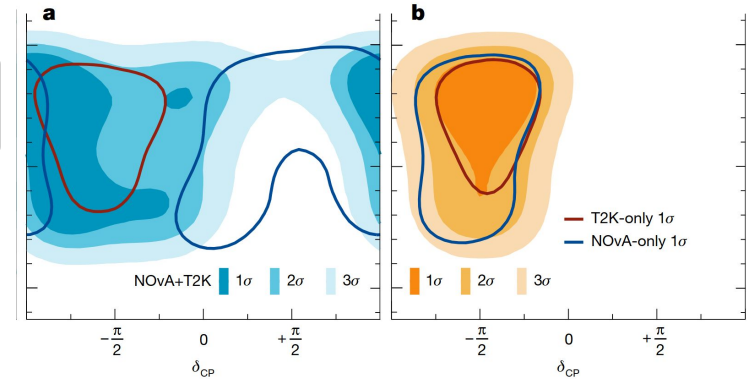
Installed six new horizontal coils in summer 2024 to restore geomagnetic field cancellation

Concept: Combine inputs from experiments that have differing and complementary properties
→ Perform a joint fit to help break degeneracies

T2K-NOvA [Nature 646, 818-824 \(2025\)](#)

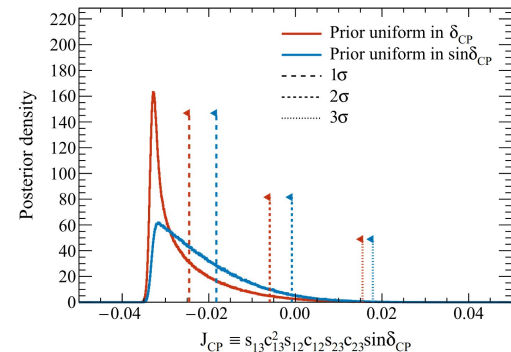
[Poster 2/#420](#)
[Poster 1/#499](#)
T2K-NOvA

- Weak preference for inverted mass ordering, where the two experiments agree well
- Weak preference for upper θ_{23} octant
- Assuming inverted ordering gives 3σ exclusion of CP-conserving values.



T2K-SK [P.R.L. 134 011801](#)

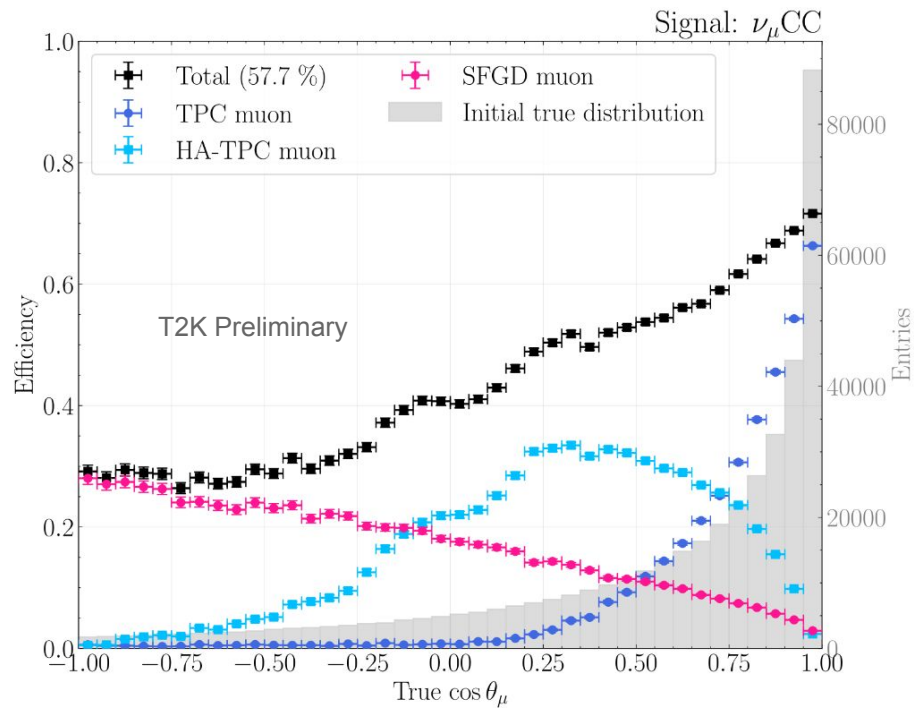
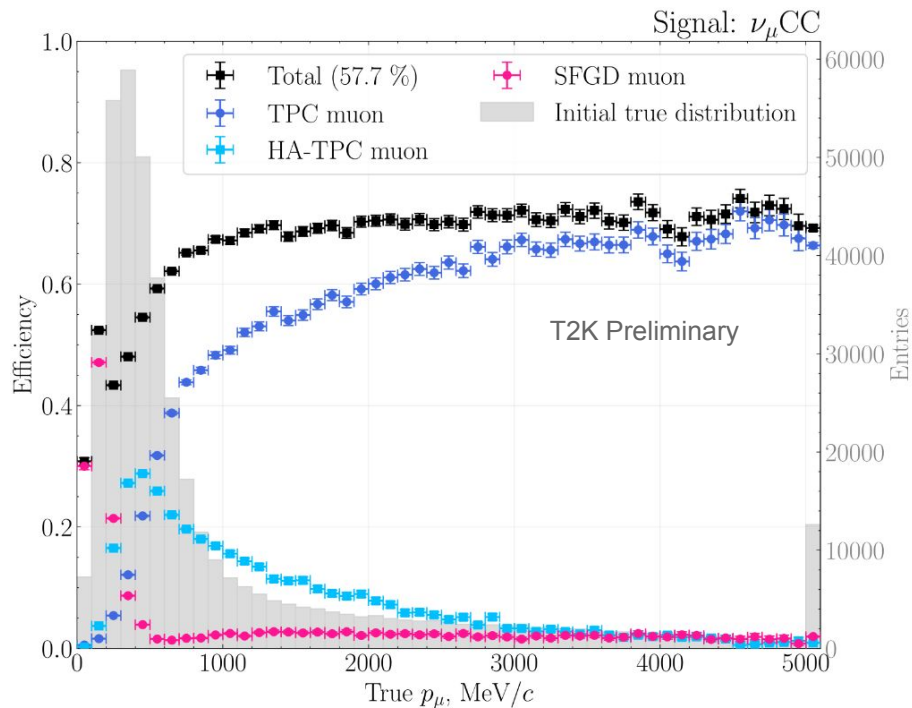
- CP-conserving values of the Jarlskog invariant are excluded with a significance between 1.9σ and 2.0σ
- 1.2σ exclusion of the inverted ordering





ND280 Upgrade Backup

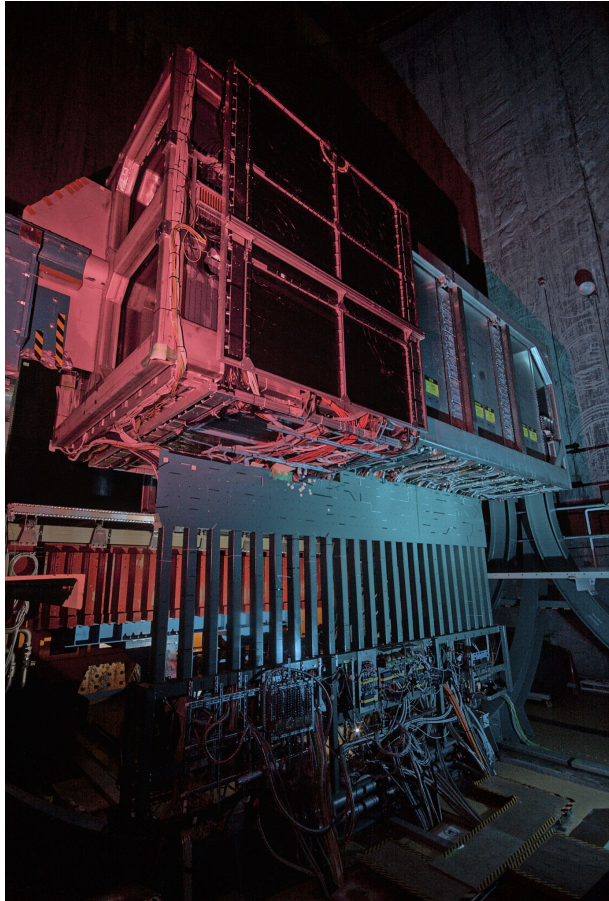
ν_μ CC Event Selection

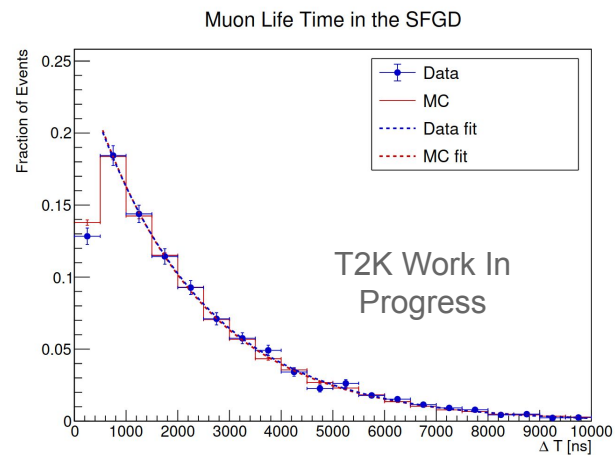
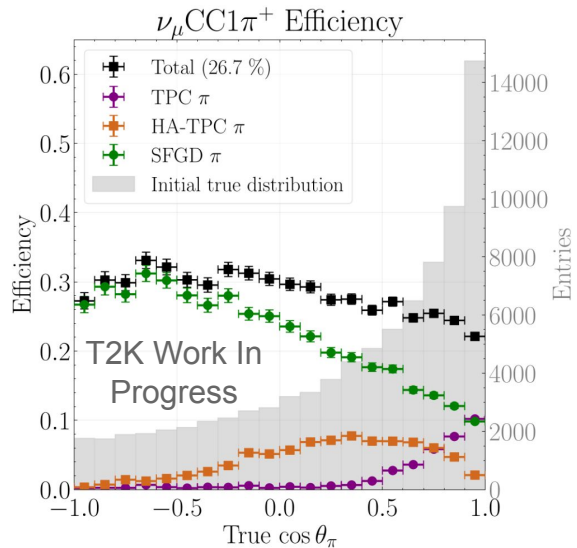
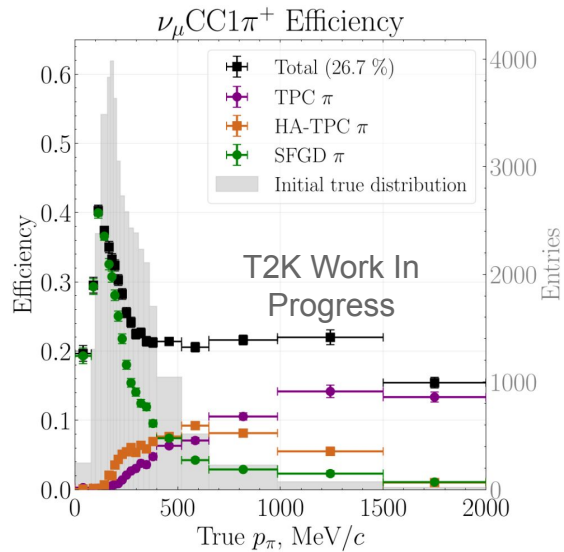


ND280 Upgrade

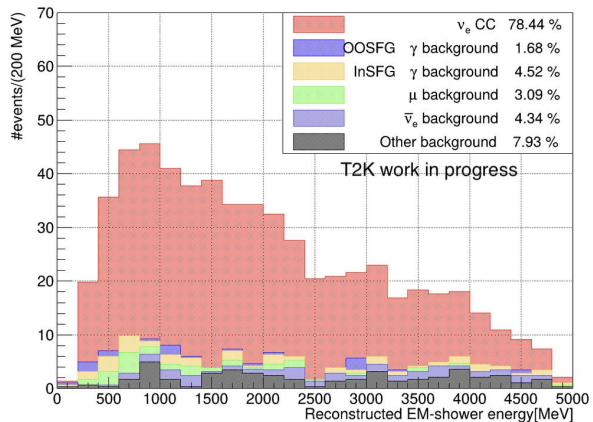


ND280 Upgrade

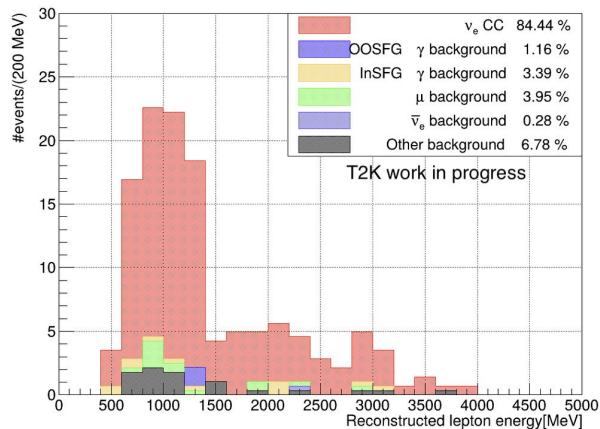




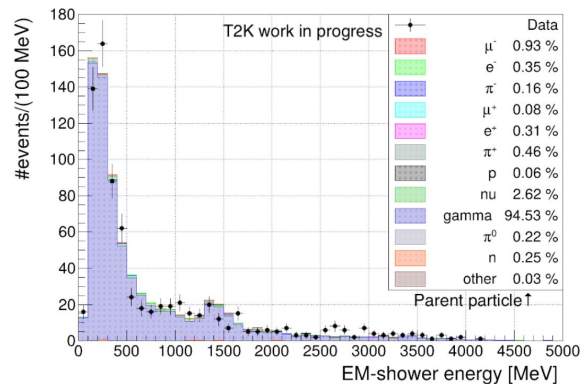
Selected events- ν_e CC with EM-shower like electron



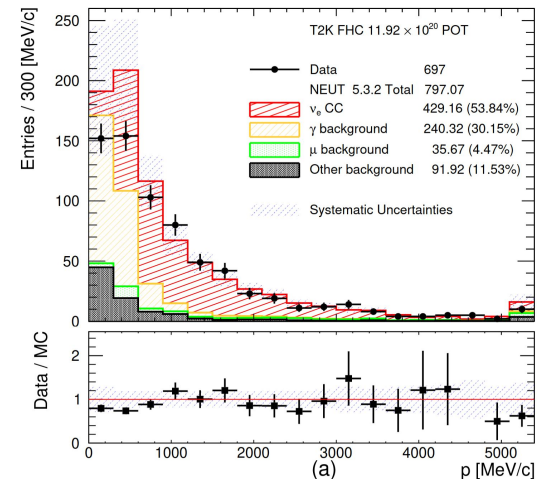
Selected events- ν_e CC with electron identified by TPC/HA-TPC



Selected events- γ sample



FGD nueCC Analysis

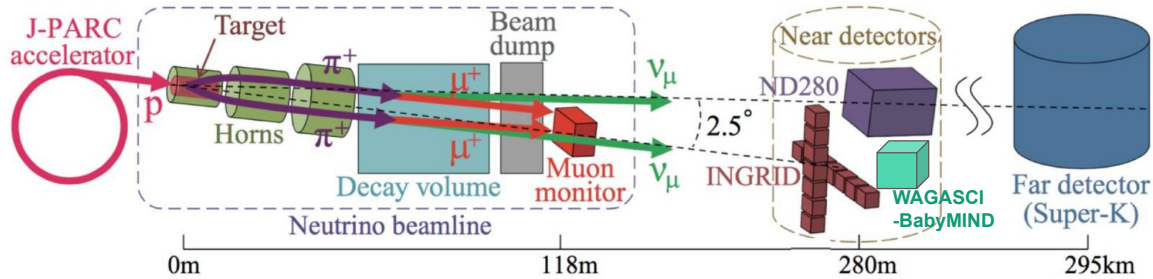




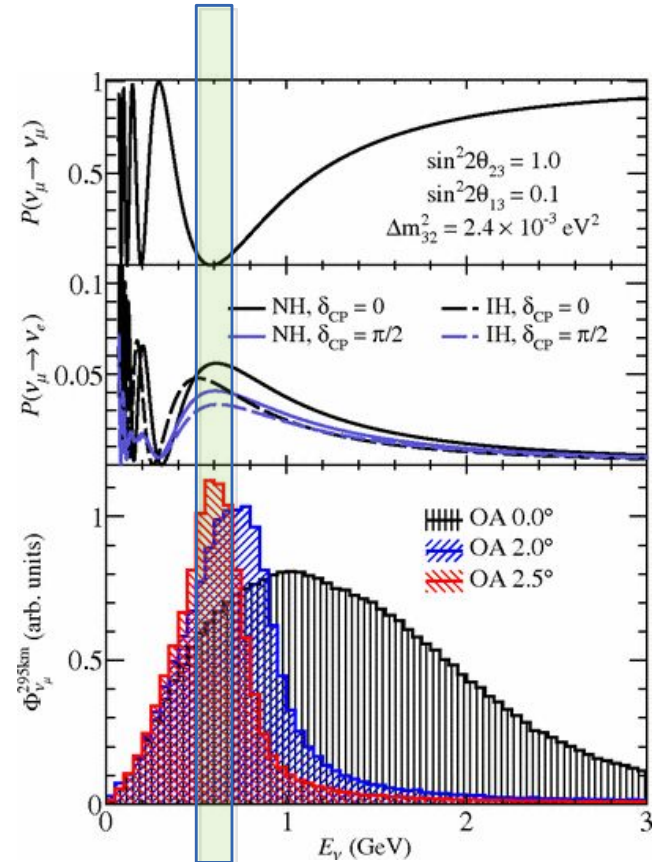
T2K

The T2K Experiment

- Long-baseline neutrino oscillation experiment



- High intensity **neutrino beam**, predominantly ν_μ ($\bar{\nu}_\mu$)
- On/Off-axis near detectors:
INGRID, **ND280**, **WAGASCI-BabyMIND**
→ unoscillated beam (280 m)
- Off-axis far detector: **Super-Kamiokande**
→ oscillated beam (295 km)



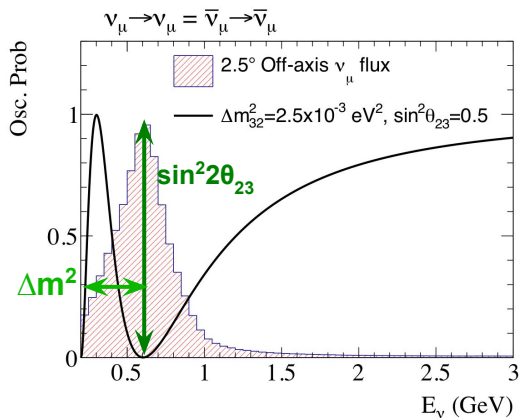
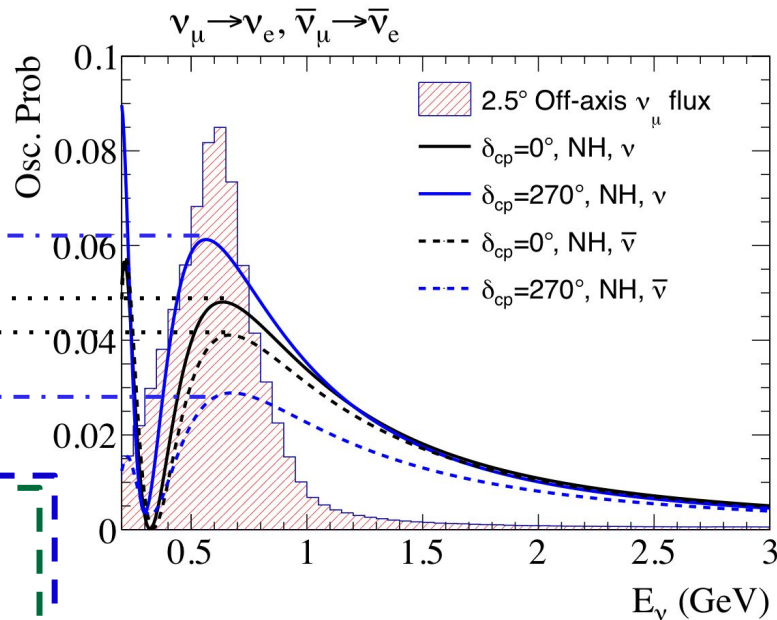
ν_e ($\bar{\nu}_e$) appearance

Probability max. causes an excess in ν_e events at SK sensitive to:

- θ_{13} , δ_{cp} , θ_{23} octant
- mass ordering

Max. effect from δ_{cp} and matter

Matter effect

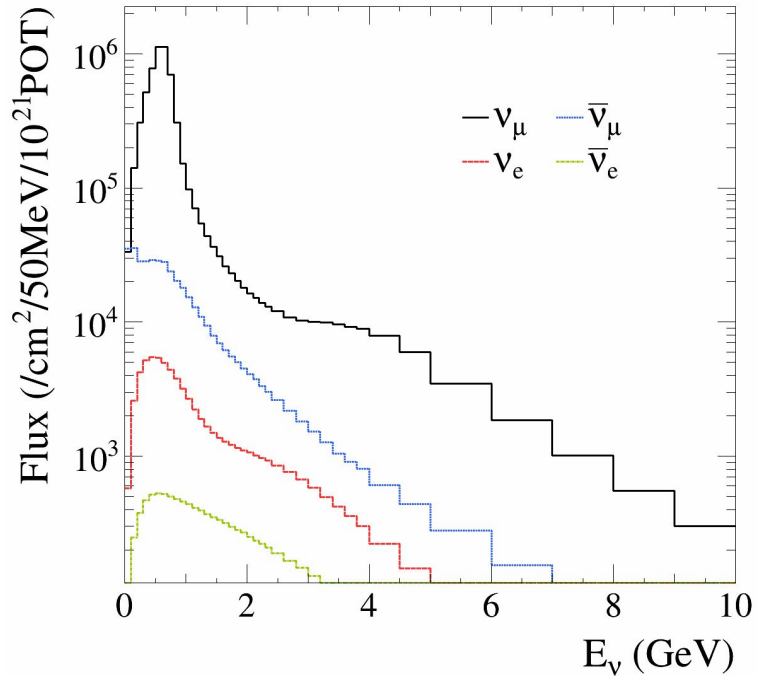


Probability min. causes a deficit in events at SK sensitive to:

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

ν_μ ($\bar{\nu}_\mu$) disappearance

Tuned run1-11 flux at SK



Tuned run5c-9d flux at SK

