Recent results and perspectives from the T2K experiment

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on behalf of the
T2K Collaboration

Neutrino Telescope 2025

Neutrino Oscillations

Neutrino Oscillations

Flavour eigenstate: Interact
Mass eigenstate: Propagate

Neutrino oscillation
→ mass states do not align with flavour states
→ non-zero masses

Oscillations governed by PMNS flavour-mass mixing matrix, U

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

Atmospheric and accelerator
$\theta_{23} \sim 45°$
$|\Delta m_{32}^2| \sim 2.5\text{x}10^{-3}$ eV^2

Reactor and accelerator
$\theta_{13} \sim 8°$
Accelerator only δ_{CP} = ??

Solar and reactor
$\theta_{12} \sim 34°$
$\Delta m_{12}^2 \sim 7.5\text{x}10^{-5}$ eV^2

Flavour states   Mass states

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

c_{ij}= cos(θ_{ij})
s_{ij}= sin(θ_{ij})

$\Delta m^2_{ij} = m^2_i - m^2_{jx}$

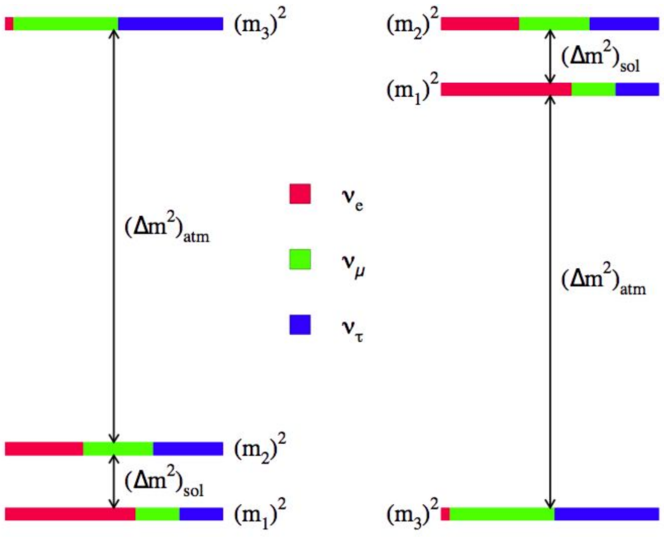
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right) + 2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

Amplitude of oscillation: **mixing angles** and **phase**

Distance of oscillation: **squared mass differences and Energy**

Remaining Questions

Mass Ordering



Normal Ordering (NO) Inverted Ordering (IO)

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})

θ_{23} octant:

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

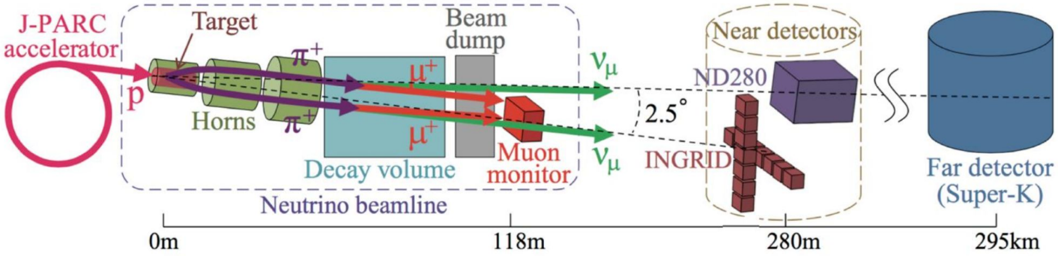
Unitarity:

Tightly constraining parameters enables tests of unitarity

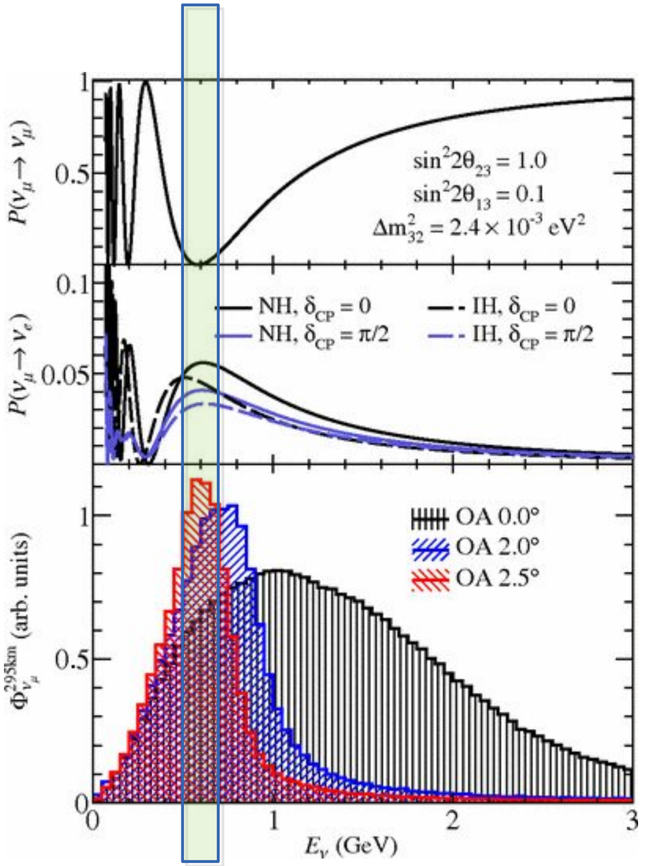
T2K

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
  → unoscillated beam (280 m)
- Off-axis far detector: Super-Kamiokande
  → oscillated beam (295 km)

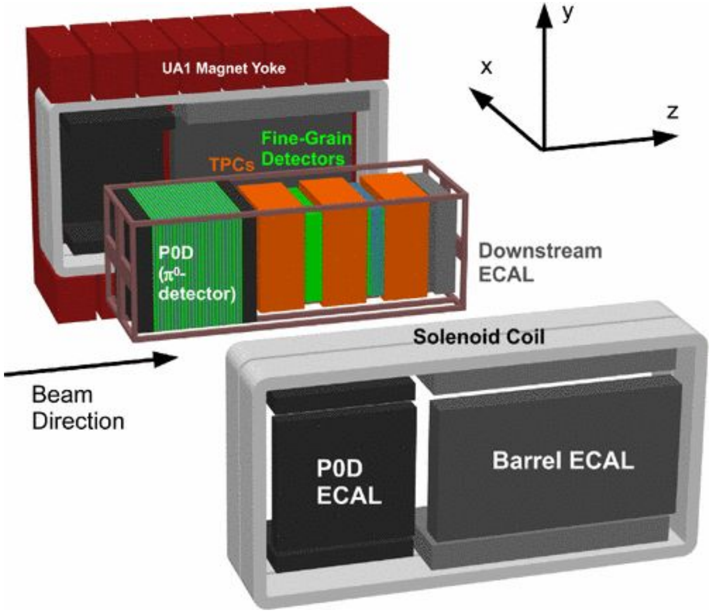


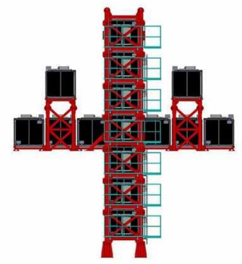
Near Detectors

ND280 - Same off-axis angle as SK

- Magnetised
- Active target mass → 2 x scintillators (**FGDs**)
  → vertex reconstruction
- 3 Time projection chambers (**TPC**)
  → **momentum** reconstruction
  → **charge** identification
  → Particle identification (**PID**)
- Electromagnetic calorimeters (**Ecal**) → **PID**
- **π^0 detector (P0D)** and **side muon range detector**

Pre-upgrade ND280



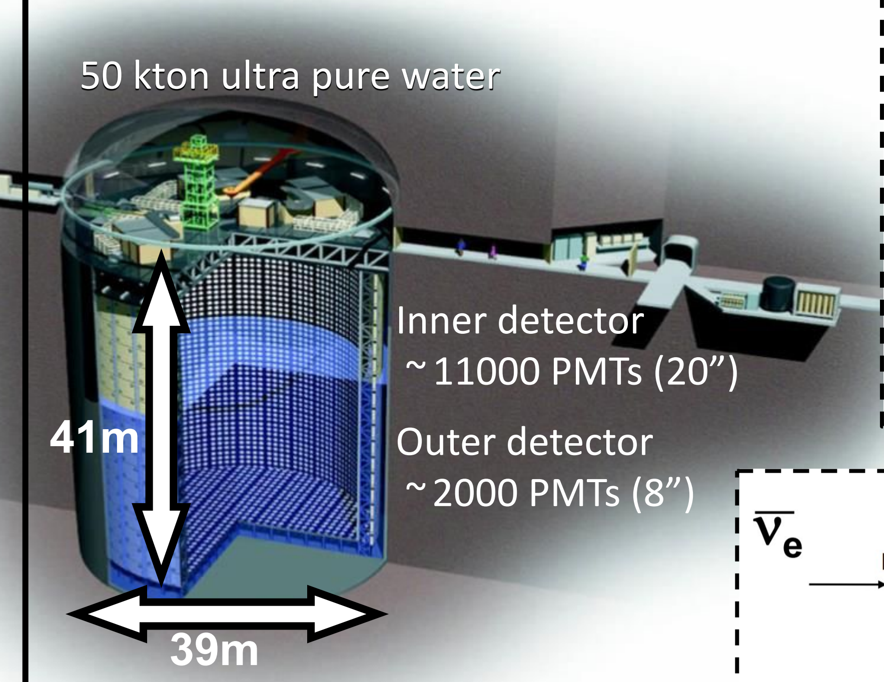


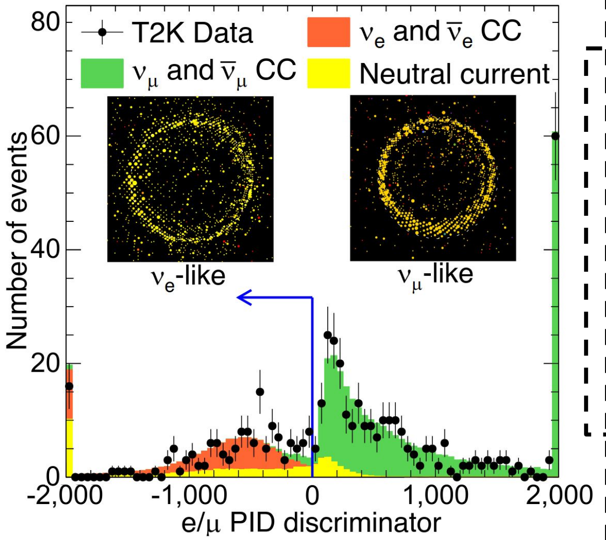
INGRID

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

Super-Kamiokande (SK)

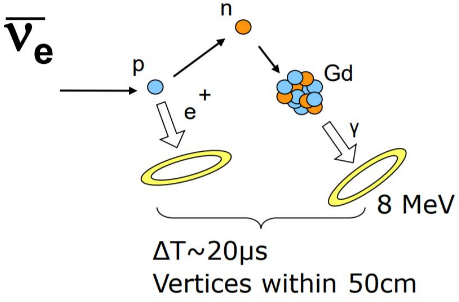
Water Cherenkov Far detector
295km from the beam source





Cherenkov rings reconstructed from PMT hit charge and time.

Excellent PID discrimination
<1% mis-PID at 1GeV



Neutron tagging gives $\nu/\bar{\nu}$ separation. SK is adding Gd to the water. Phase I reached 0.01%, and Phase II is at 0.03% which gives ~75% neutron tagging efficiency.

Next talk by Lucas Machado:
Recent results from the Super-Kamioka Experiment

T2K Oscillation Analysis

ν_e ($\bar{\nu}_e$) appearance

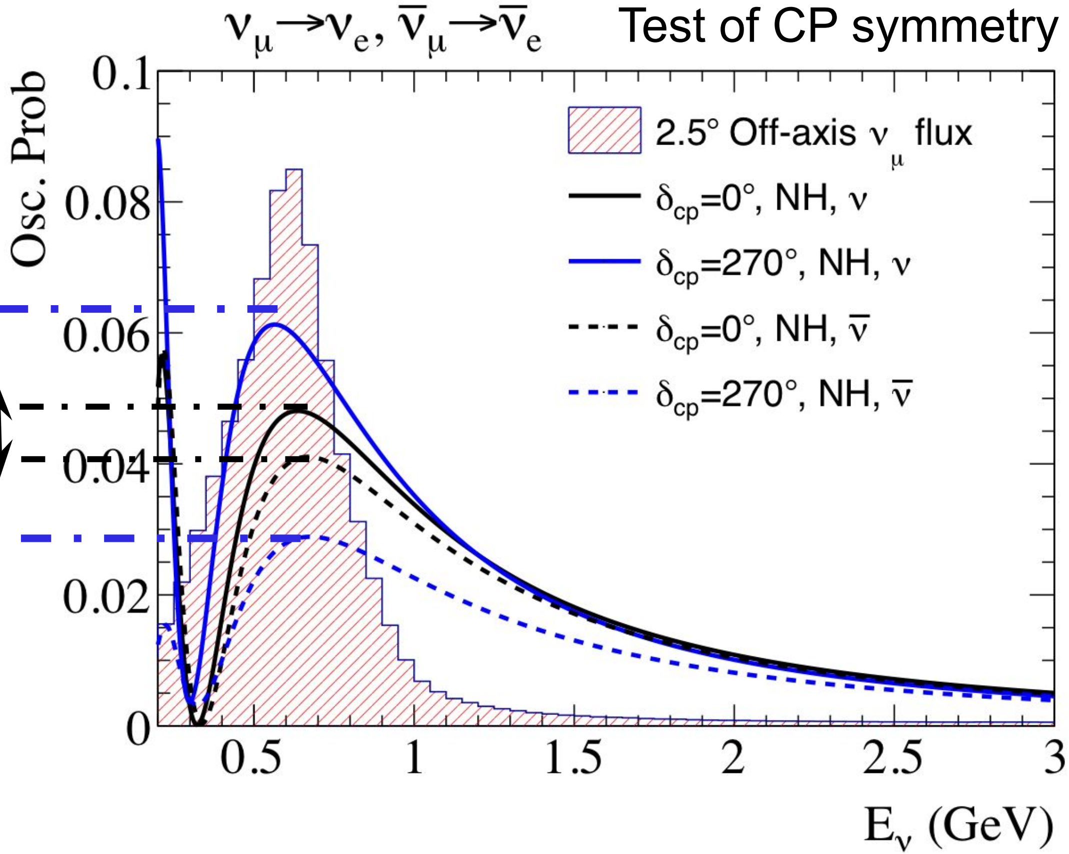
Probability maximum causes an excess in events at SK

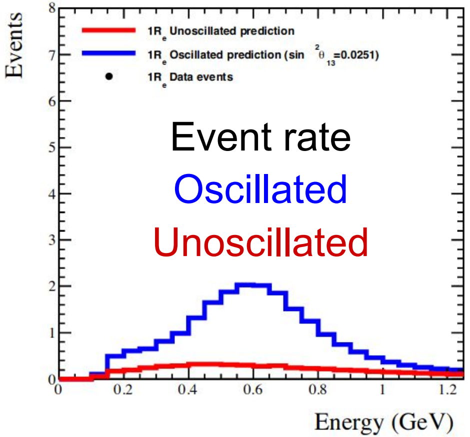
- θ_{13} , δ_{cp}
- Mass ordering
- θ_{23} octant

Test of CP symmetry

Maximum effect from δ_{cp} and matter

Matter effect

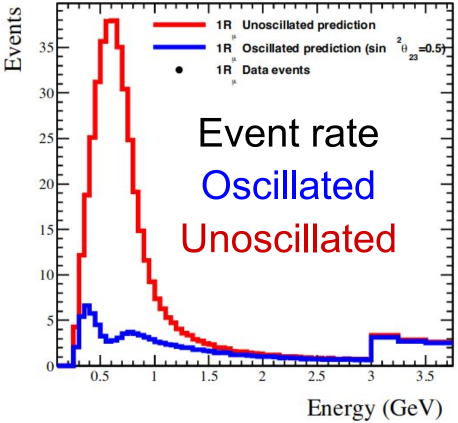




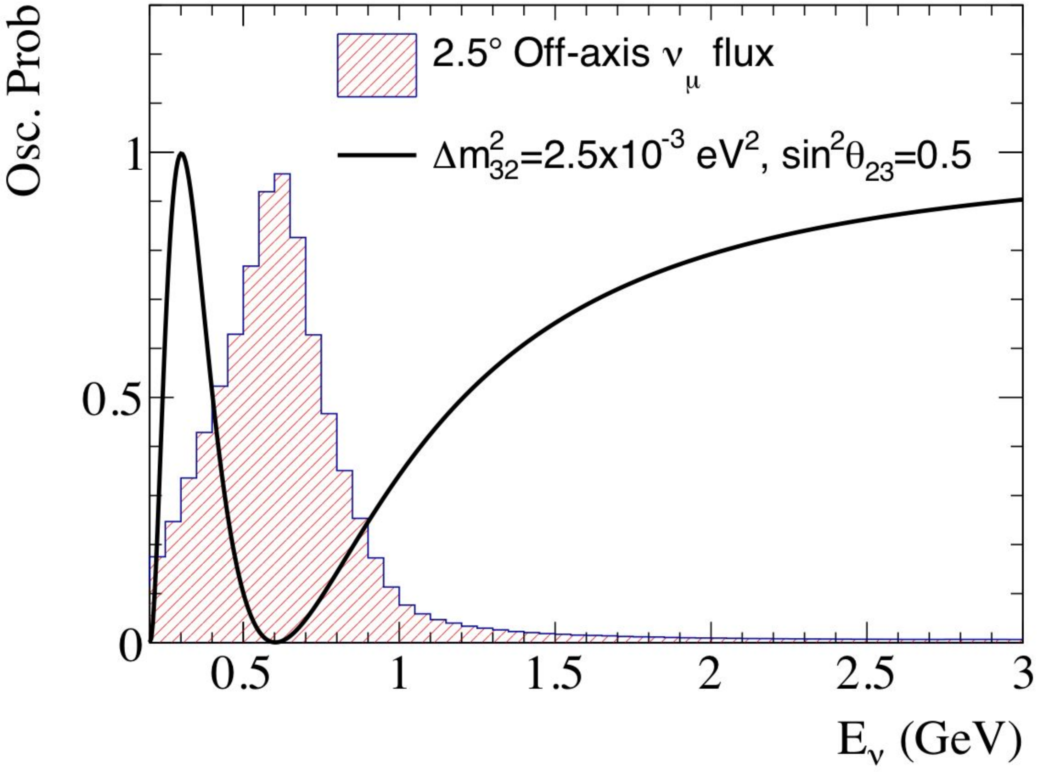
ν_μ ($\bar{\nu}_\mu$) disappearance

Probability minimum causes a deficit in events at SK

- Depth of dip
  - $\sin^2(\theta_{23})$
- Energy of dip
  - $|\Delta m^2_{32}|$ ($|\Delta m^2_{13}|$)



$\nu_\mu \rightarrow \nu_\mu = \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ Test of CPT symmetry

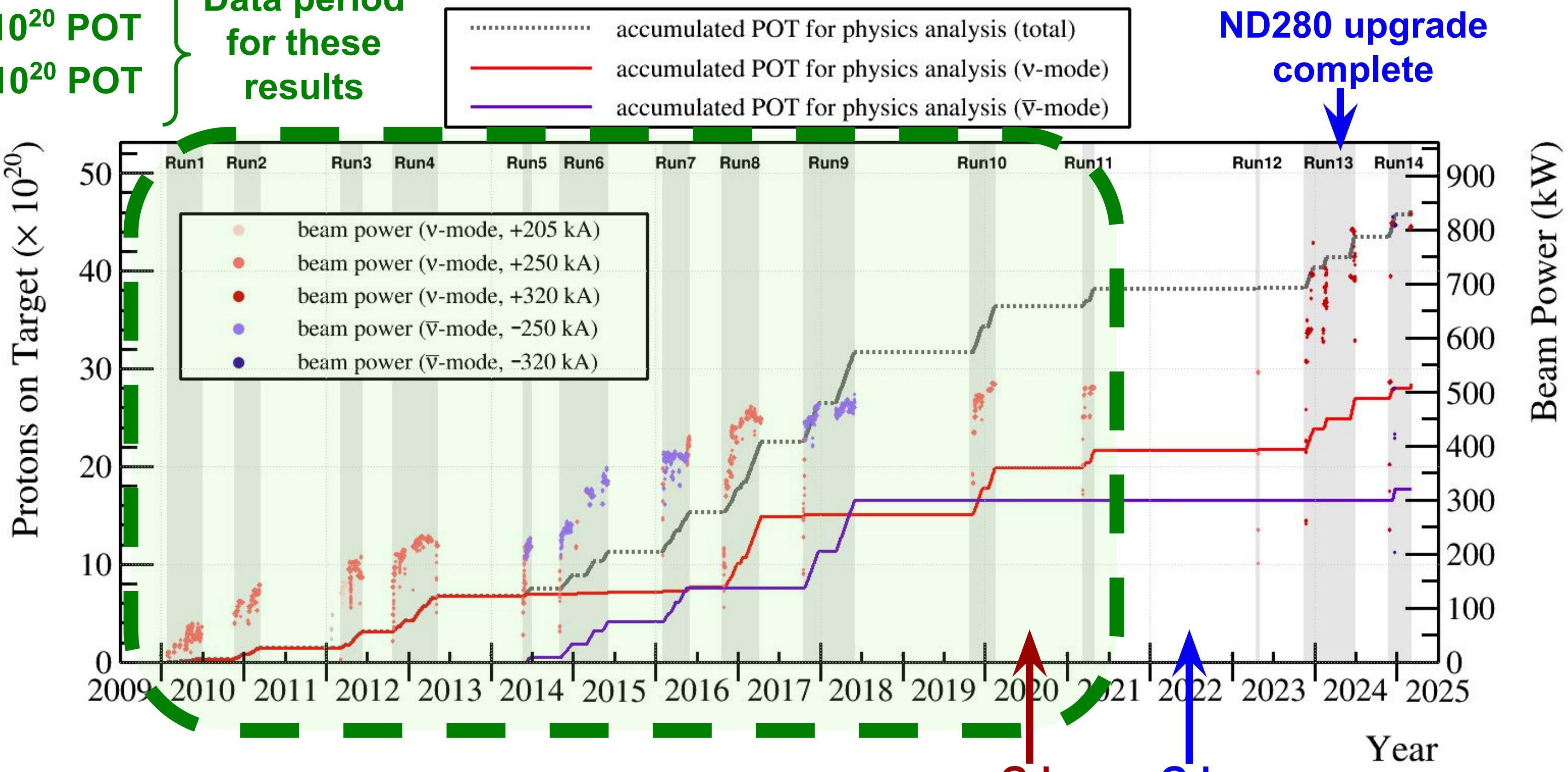


T2K Protons on target (POT)

ν: 21.4x10^{20} POT
$\bar{\nu}$: 16.3×10^{20} POT

Data period for these results

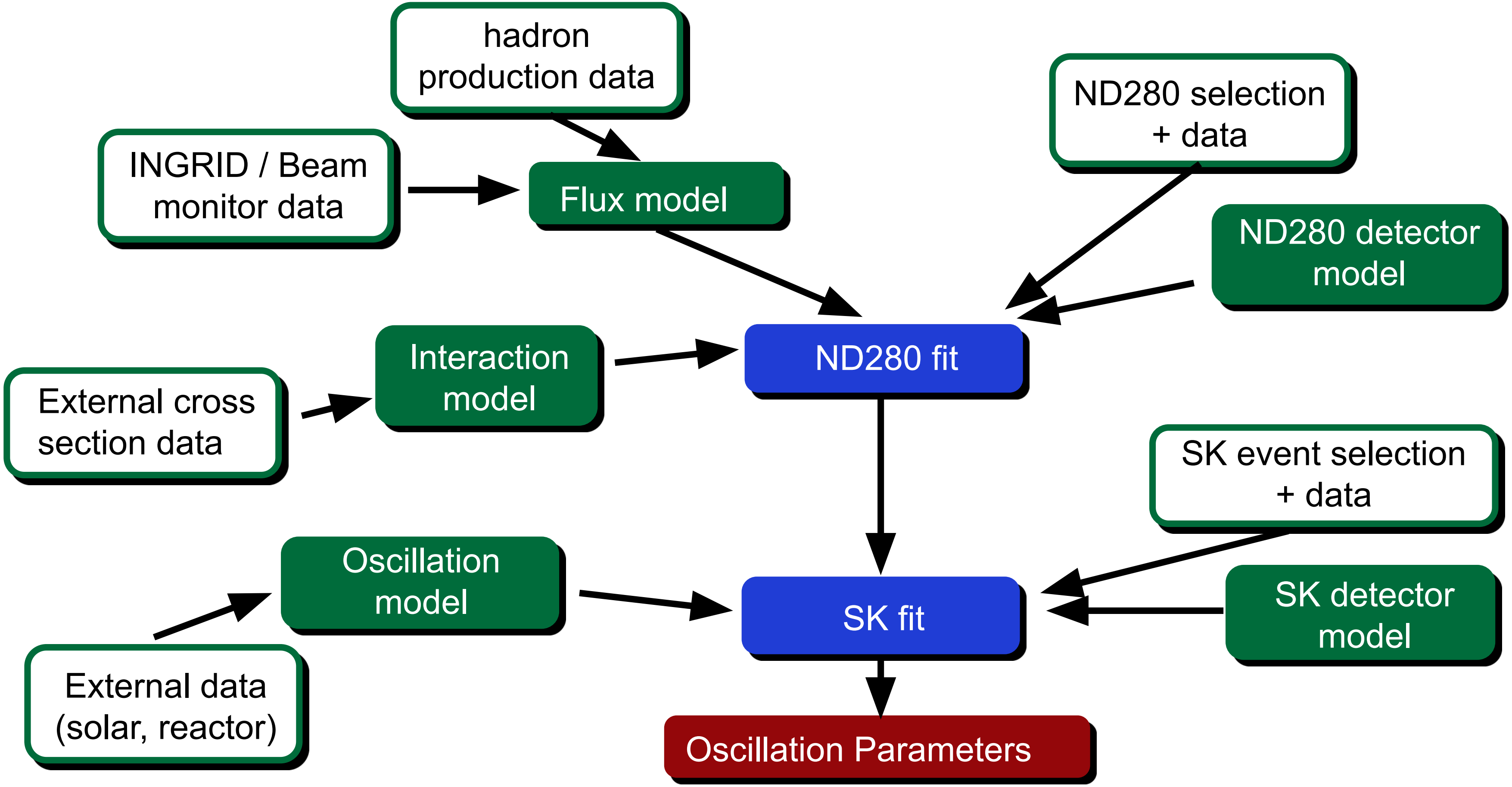
ND280 upgrade complete



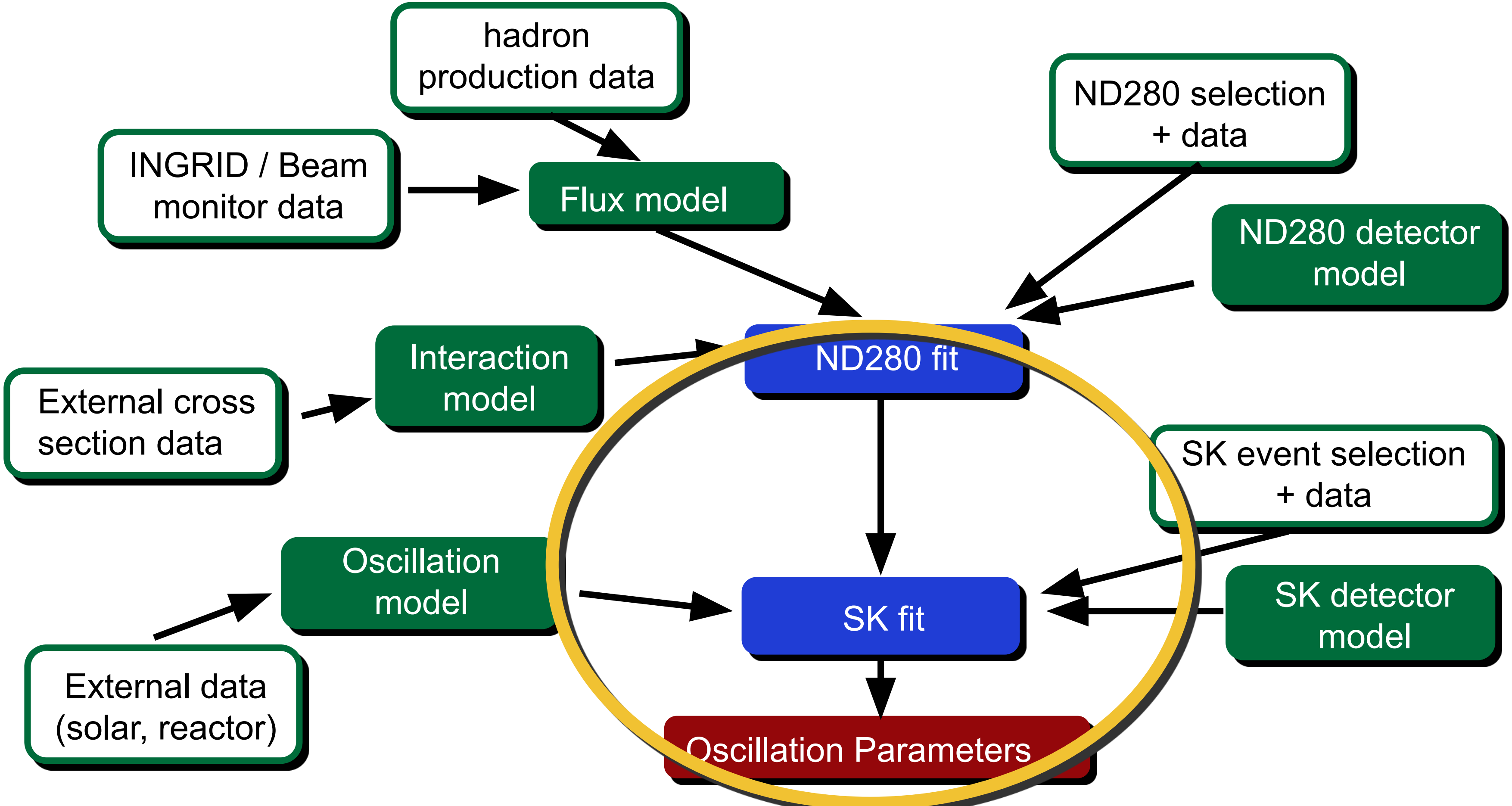
Gd 0.01%

Gd 0.03%

Oscillation Analysis



Oscillation Analysis



Oscillation Analysis

Analysis 1: Frequentist

- Two stage fit: An independent near detector (ND280) fit is performed, and the result is then fed into the far detector (SK) oscillation fit.
- Frequentist methods using marginal likelihood.
- Feldman-Cousins method used to obtain confidence levels

Analysis 2: Bayesian

- Simultaneously fit: Both the near (ND280) and far detector (SK) data goes into a single fit to constrain the oscillation parameters.
- Bayesian methods using Markov Chain Monte Carlo.
- Credible intervals obtained from the posterior distributions.

hadron

IN
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External
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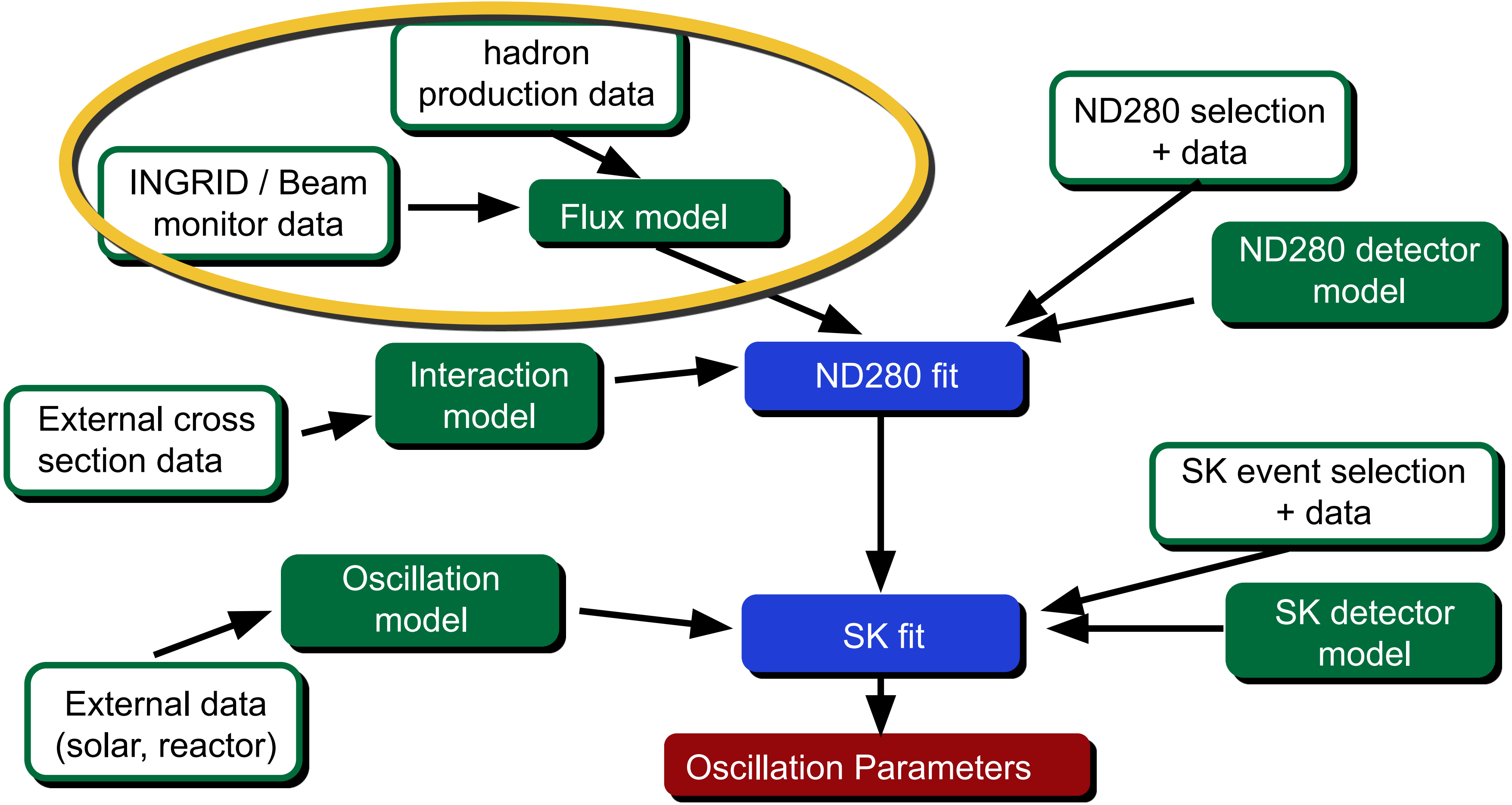
Extern
(solar, reactor)

ND280 fit

SK fit

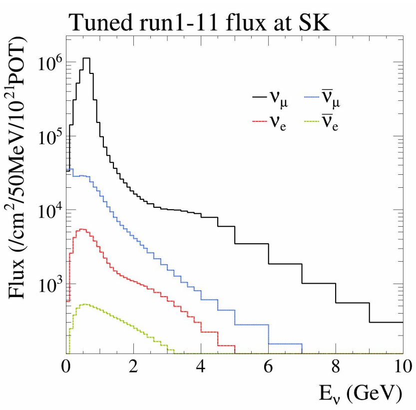
Oscillation Parameters

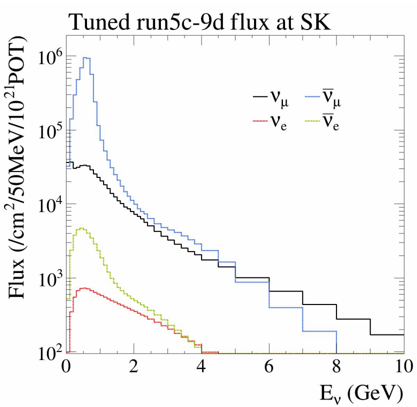
Oscillation Analysis

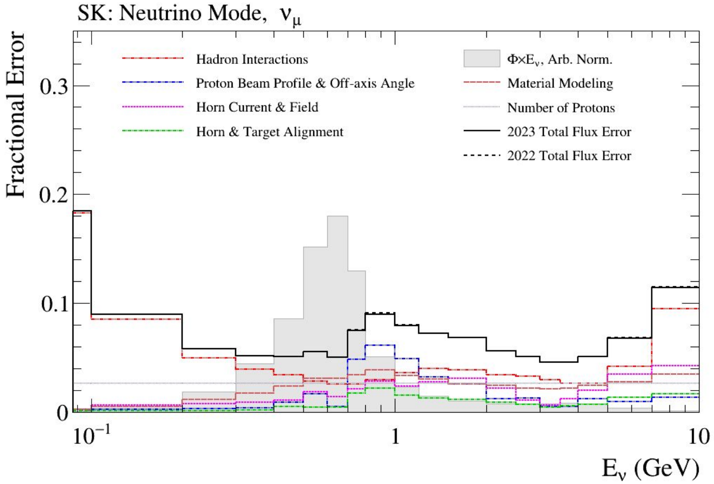


T2K Flux

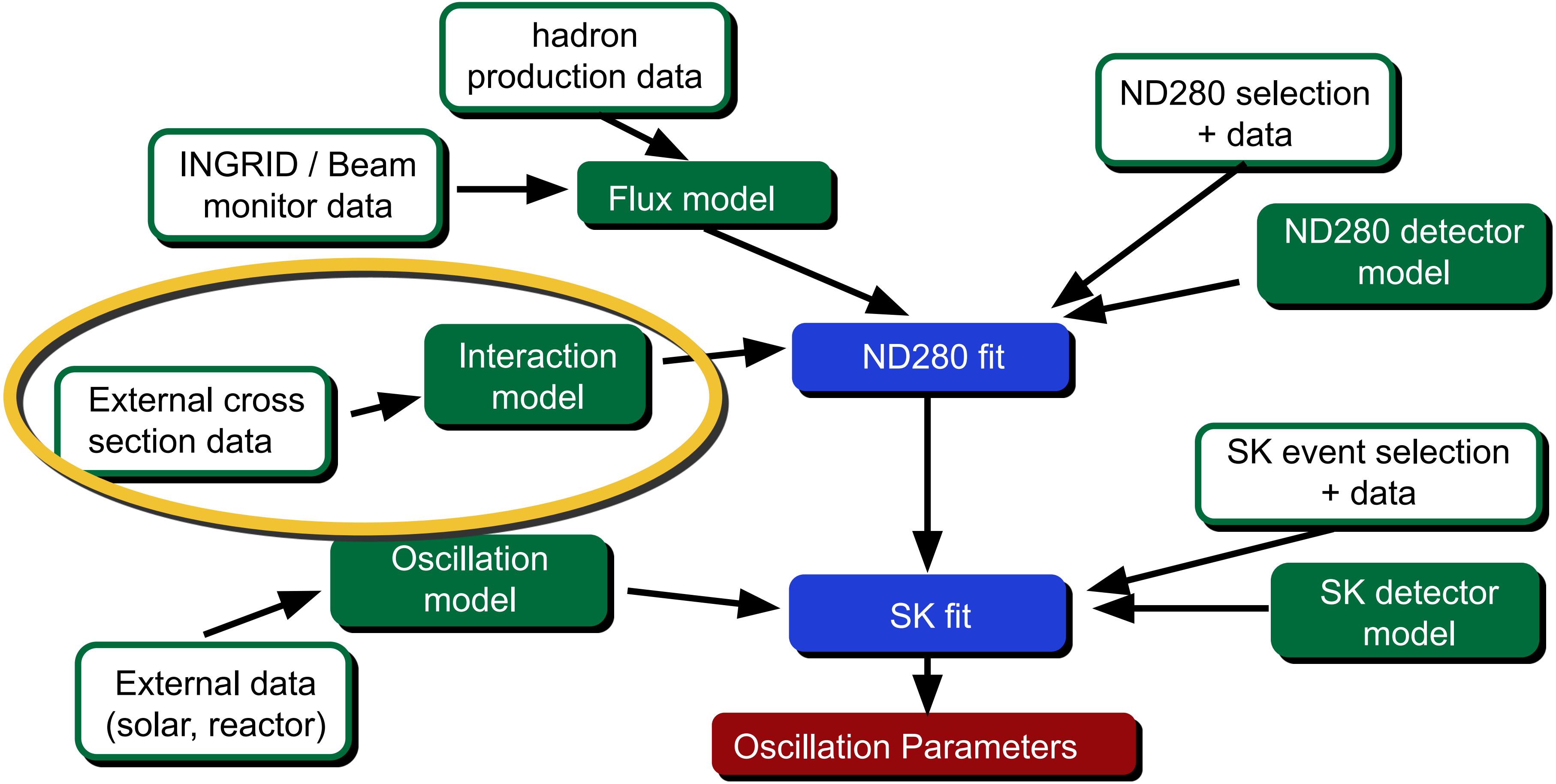
* **30GeV protons** → **graphite** target → charged **hadrons**
* **charge selection** and focusing of hadrons with **3 electromagnetic horns**
* **hadrons decay to ν or $\bar{\nu}$** depending on charge
* INGRID and the Muon Monitor continuously measure beam intensity, profile and direction
* **Dominant systematic error due to hadron interaction modelling**
  → Tuned using NA61/SHINE T2K target replica measurements
  → Reduces error from ~ 20% →5% around the peak
* The flux is further constrained by ND280 data in the fit







Oscillation Analysis

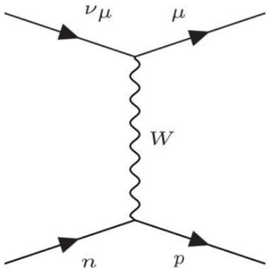


Neutrino Interaction Modelling

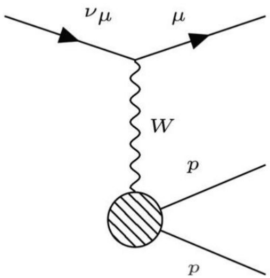
T2K energies are dominated by CCQE.

Significant contributions also come from 2p2h and resonant interactions

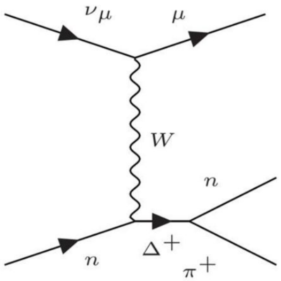
CC-QE
(Quasi-elastic)



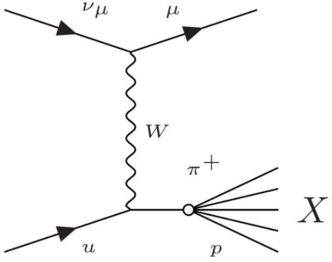
CC-2p2h
(Two-Particle-Two-Hole)

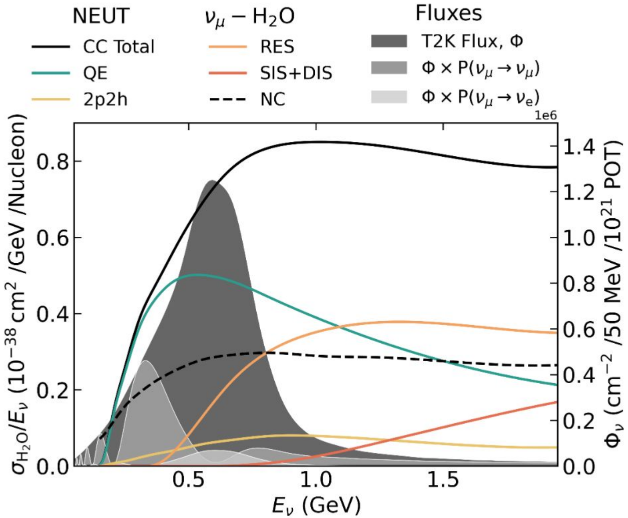


CC-Resonant 1π



CC-DIS
(Deep Inelastic Scattering)

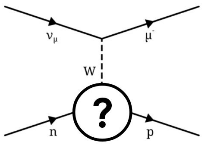




Interactions occur with nucleons bound inside a nucleus → Nuclear effects!

CC-0π

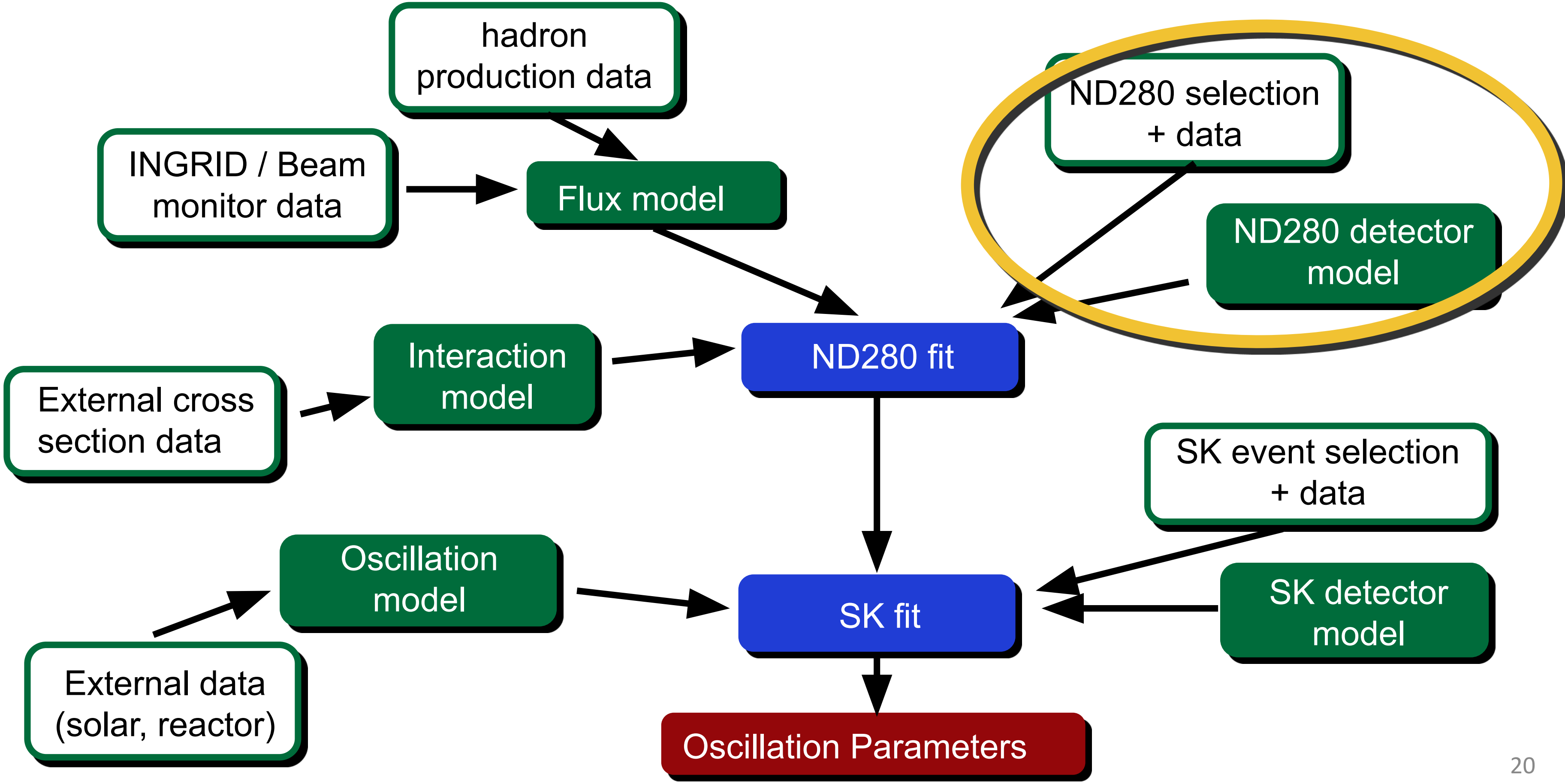
e.g. FSI



Mis-modeling of interaction channel contributions can bias neutrino energy reconstruction

T2K uses external constraints and the near detector to constrain the interaction model and reduce uncertainties.
→ Important to have advanced models with the required freedom.

Oscillation Analysis



ND280 Inputs

All Reconstructed Events

ν-beam: ν_μ CC-Inc (FGD1 and FGD2)
↓
CC0π-0p-0γ
CC0π-Np-0γ
CC1π^+-0γ
CC-Other-0γ
CC-Photon

$\overline{\nu}$-beam: $\overline{\nu}_\mu$ CC-Inc (FGD1 and FGD2)
↓
CC0π
CC1π^-
CC-Other

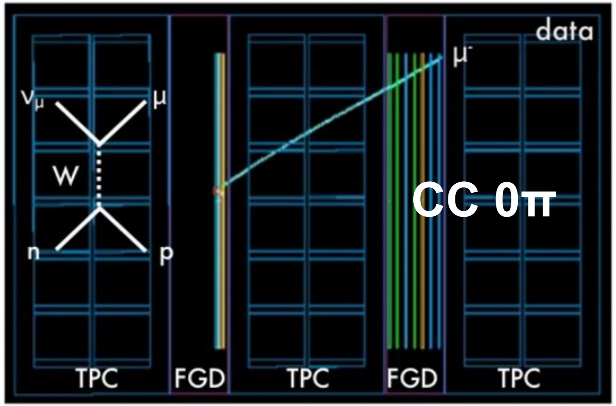
$\overline{\nu}$-beam: ν_μ CC-Inc (FGD1 and FGD2)
↓
CC0π
CC1π^+
CC-Other

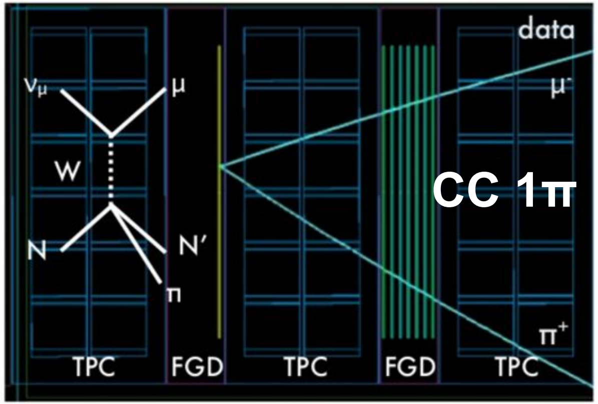
FGD1:

- Carbon

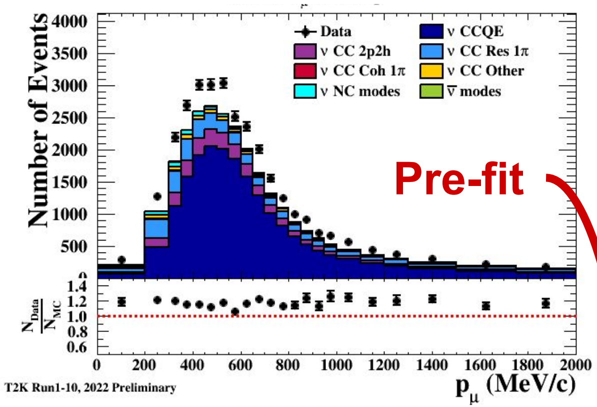
FGD2:

- Carbon
- Water (target in far det)



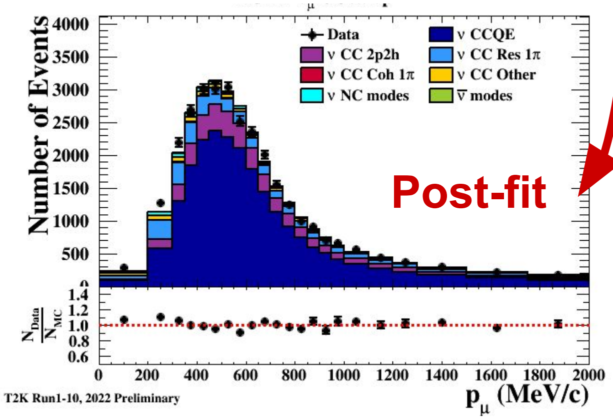


ND280 Fit

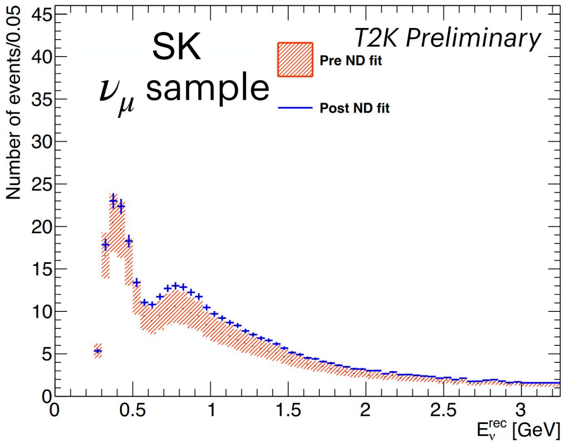


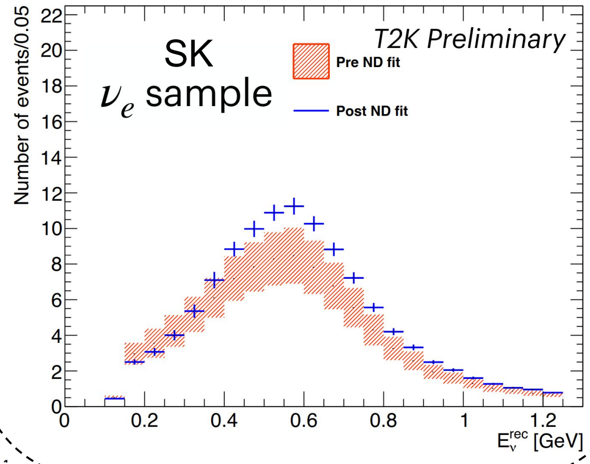
Pre-fit

ND280 FGD1 ν_μCC 0π0p



Post-fit



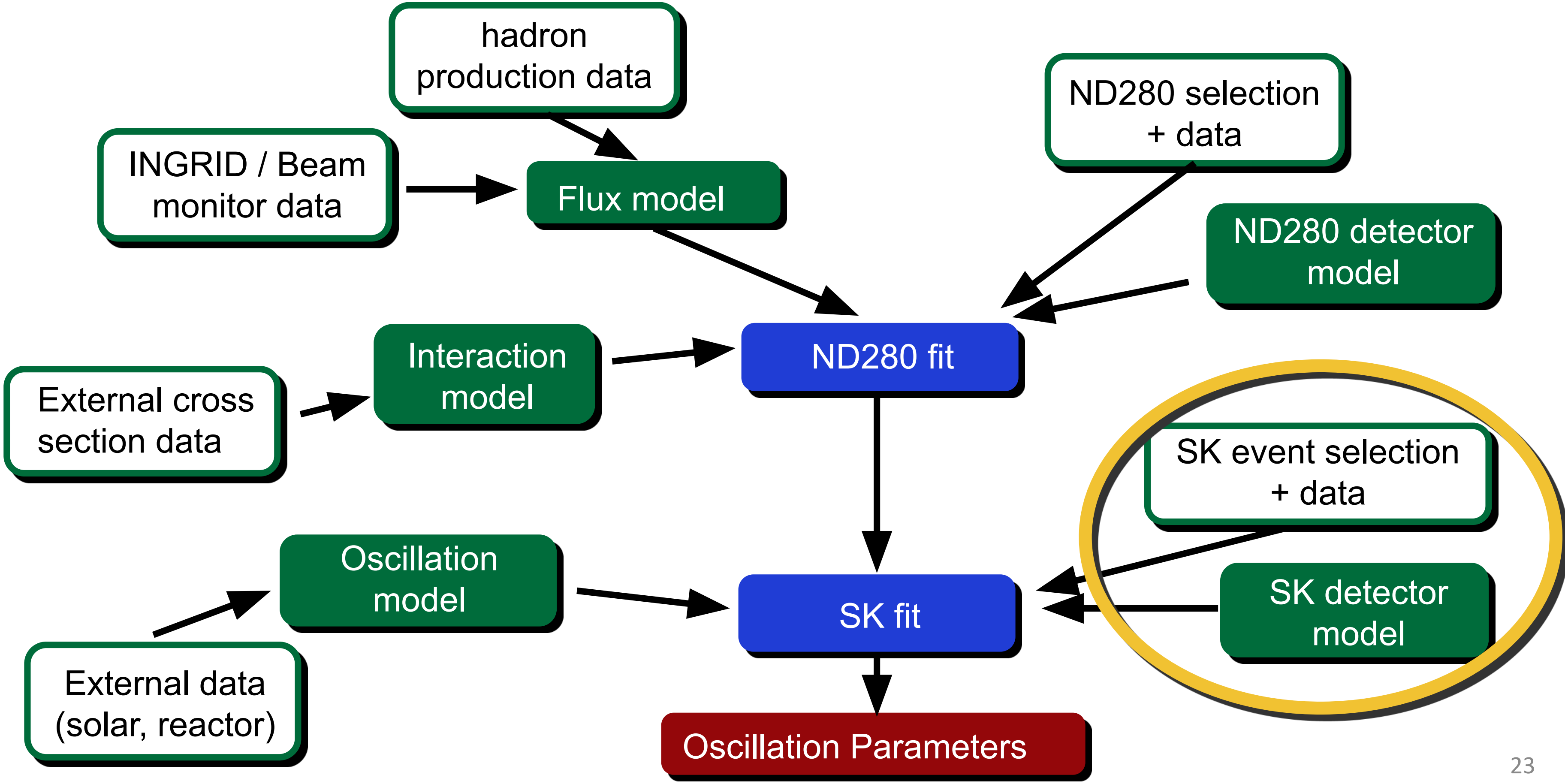


The ND280 fit reduces the error on the number of events selected at SK

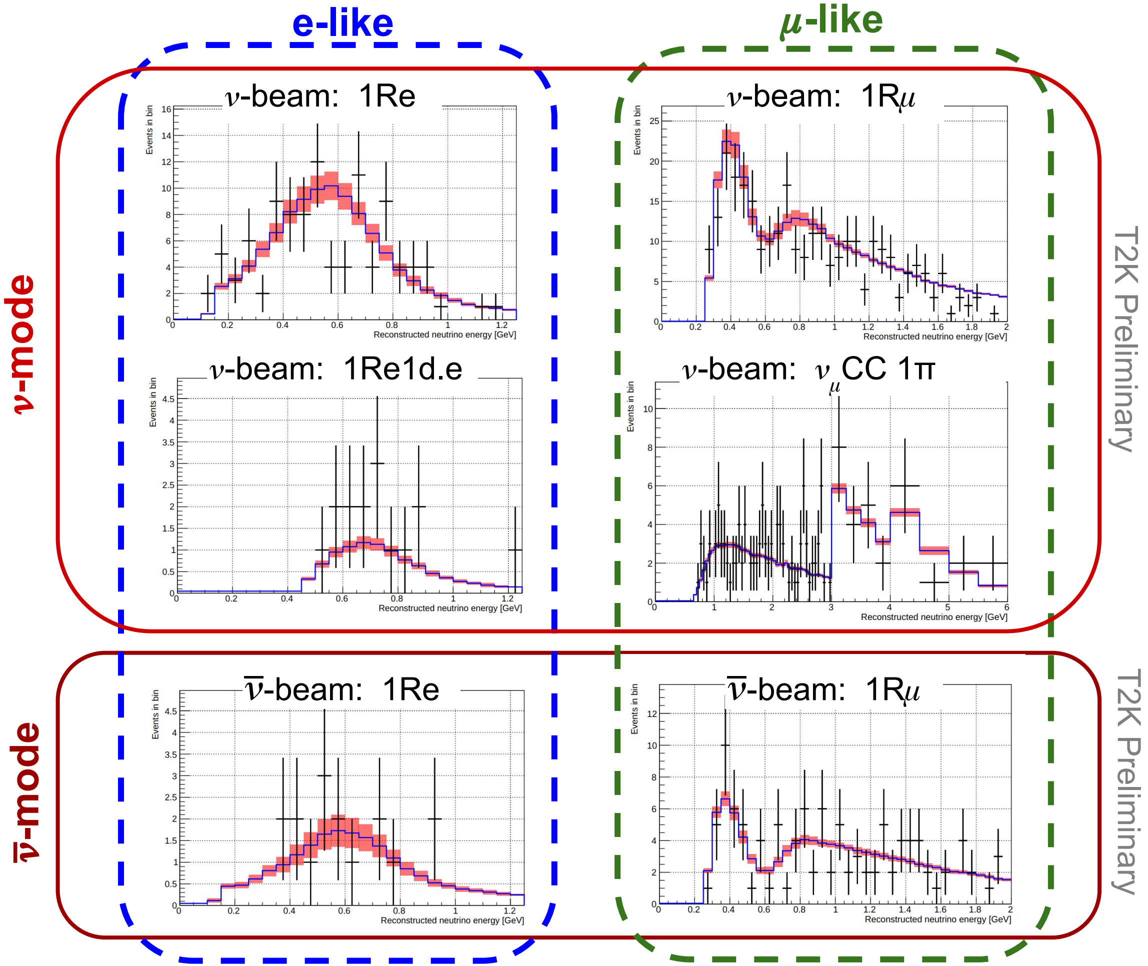
$\sim 17\% \xrightarrow{\nu_\mu} \sim 3\%$

$\sim 17\% \xrightarrow{\nu_e} \sim 5\%$

Oscillation Analysis



SK Event Samples

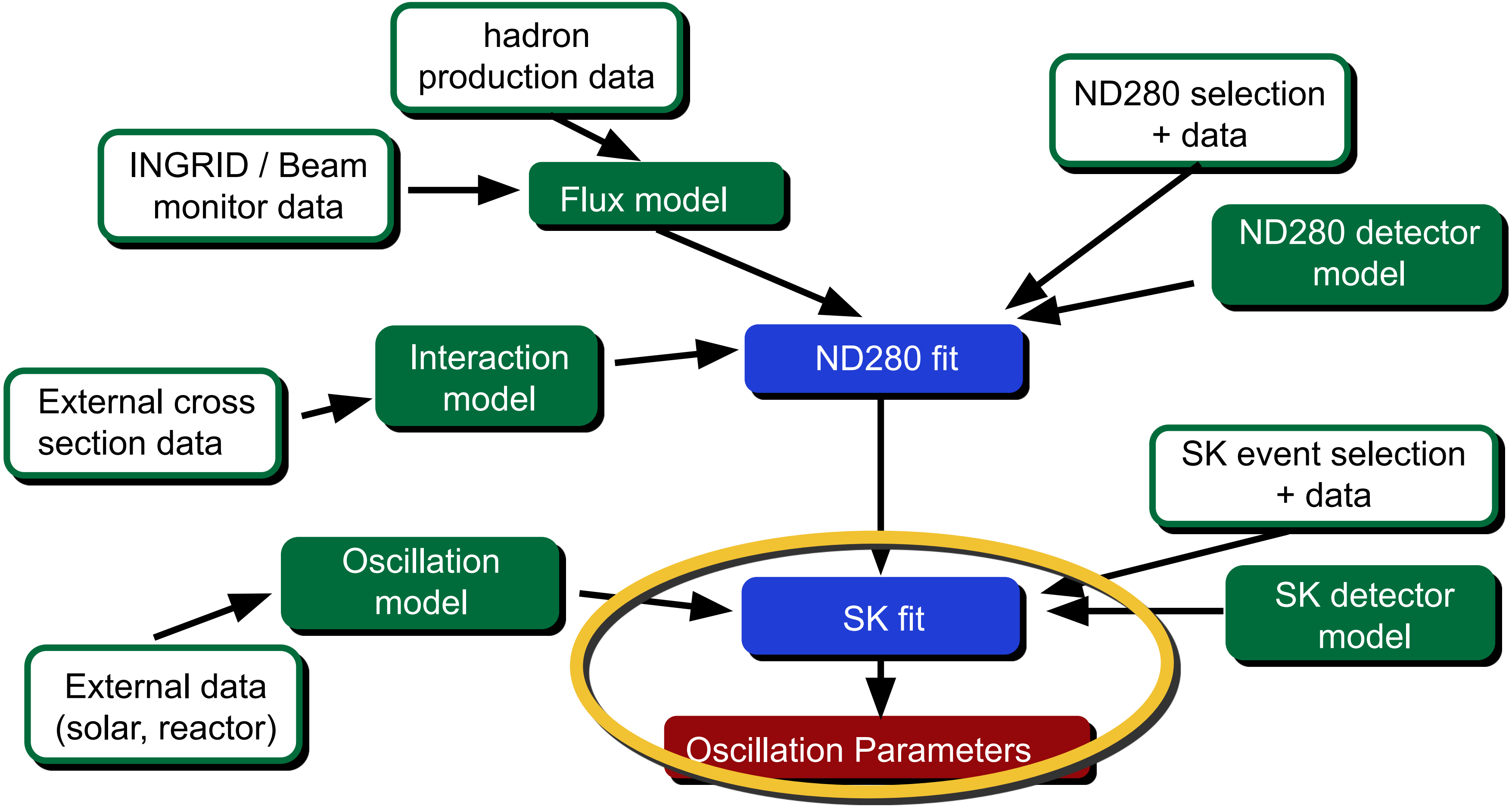


Re - Ring electron
Rμ - Rung muon
d.e - Decay electron

Updates since previous analysis

- Additional ~10% of SK data
- First data included from Gd phase I (0.01% Gd)
- Improved decay electron tagging.
- UpdatedSK detector systematics. Significant error reduction for 1Re 1d.e.

Oscillation Analysis



T2K Oscillation Analysis Results

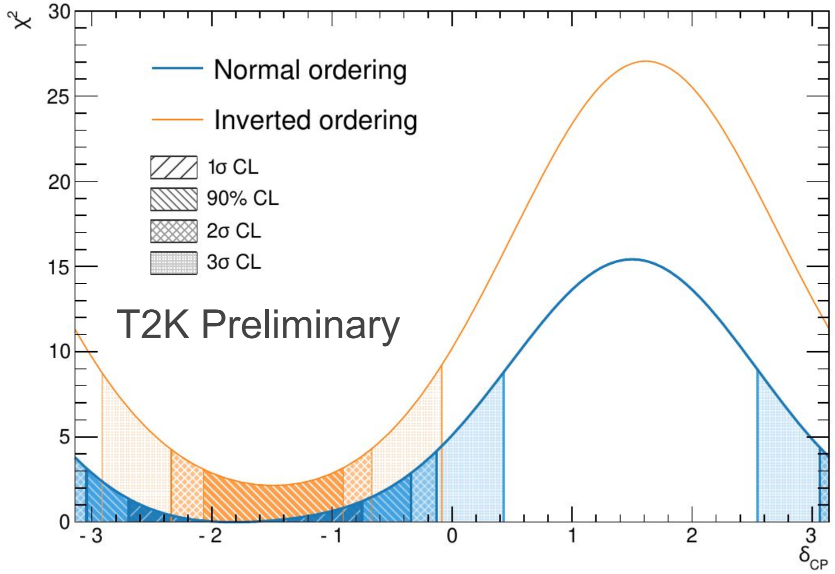
The T2K oscillation results:

- Have gaussian priors on Δm^2_{21} and $\sin^2(\theta_{12})$ taken from PDG values
- Have a prior on θ_{13} taken from constraints from reactor experiments

Results - δ_{cp}

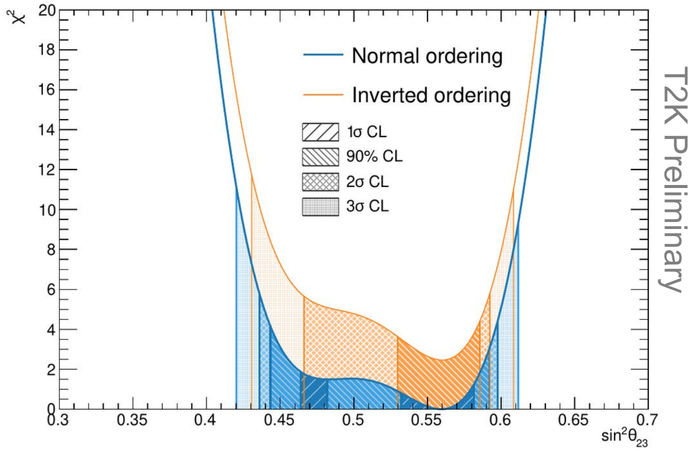
- CP conservation is excluded with 90% confidence level (C.L.) for the nominal analysis.
- To test the robustness of our result, 18 additional models are tested and compared with the nominal analysis. → two do not exclude CP conservation at 90% CL.

Frequentist analysis



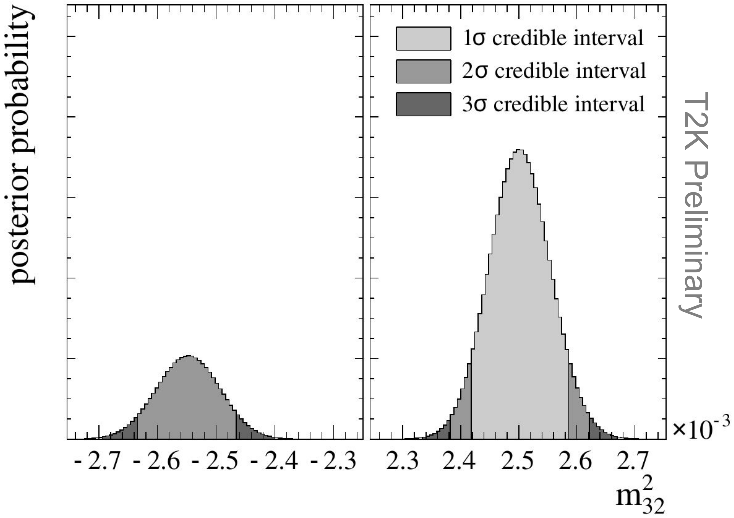
Results - θ_{23}, Δm^2_{32}

Frequentist analysis



Weak preference for normal ordering. Preference for upper octant for both mass orderings, but both octants are allowed within the 1σ CL.

Bayesian analysis



Weak preference for normal ordering. This preference is there without the reactor constraint, and then strengthened when included.

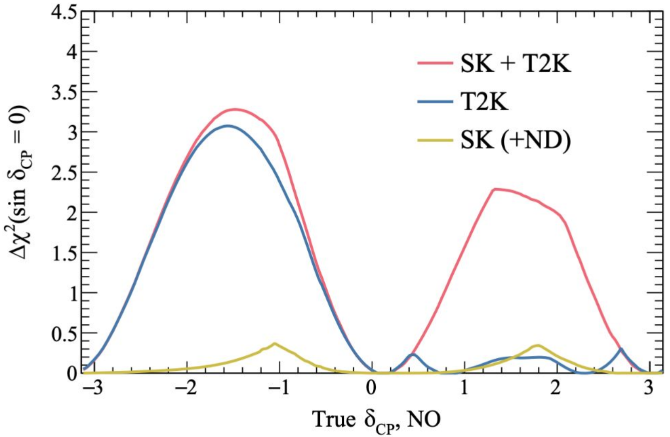
Joint Analysis

Note: To hear more about SK, please see the next talk in the session by Lucas Machado:
Recent results from the Super-Kamioka Experiment

T2K + SK Joint Analysis

Combined fit using

- T2K Beam data (better δ_{cp} sensitivity)
- SK atmospheric data (better mass ordering sensitivity)



The use the same far detector

→ Where appropriate, unify the model for neutrino interactions and for detector systematics

T2K Beam and SK Atmospheric have complementary inputs

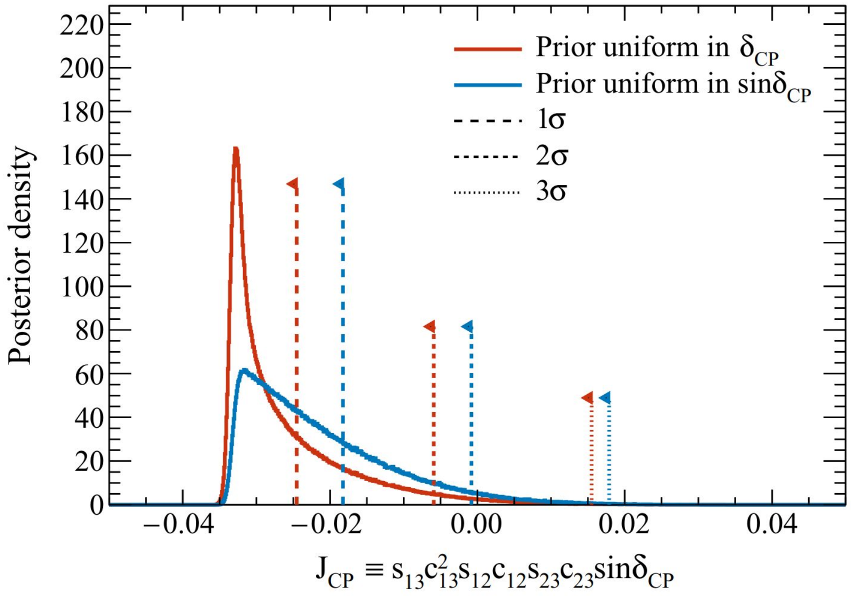
- Different (but overlapping) energy spectra, baselines, matter effects

This is the first time that the two collaborations have combined their data to produce a joint result

→ Combing these data sets helps to break degeneracies, in particular between δ_{cp} and mass ordering, to give improved δ_{cp} constraints

T2K + SK Joint Analysis

https://doi.org/10.1103/PhysRevLett.134.011801



- CP-conserving values of the Jarlskog invariant are excluded with a significance between 1.9σ and 2.0σ
- Limited preference for the normal ordering with a 1.2σ exclusion of the inverted ordering
- No strong preference for the θ_{23} octant.

This first joint analysis is an important step toward the combined beam and atmospheric data analyses planned by next-generation neutrino oscillation experiments.

Joint Analysis

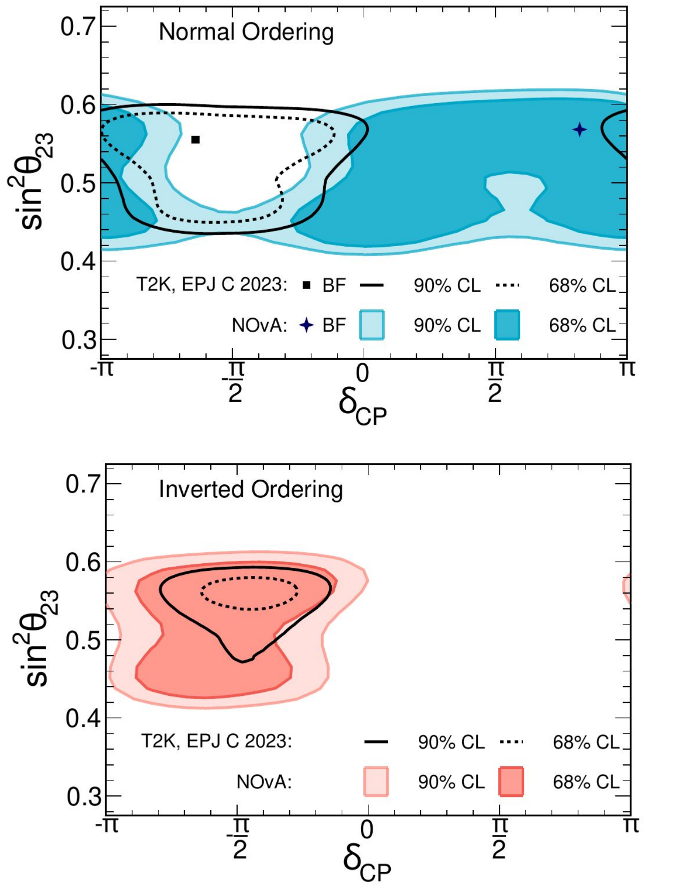
T2K + NOvA Joint Analysis

T2K and NOvA have complimentary properties and capabilities

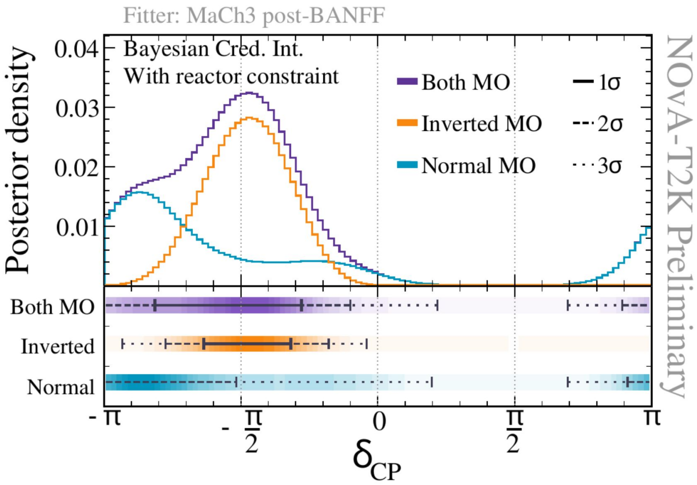
Experimental Property	T2K	NOvA
Proton beam	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection tech	FGD and Water Cherenkov	Segmented Liq scin. bars
CP effect	32%	22%
Matter effect	9%	29%

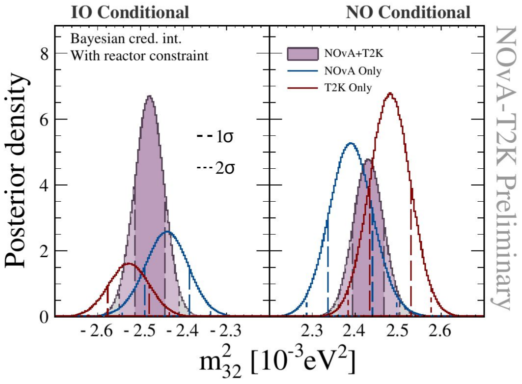
Combining inputs from both experiments to form a combined fit can help to break degeneracies.

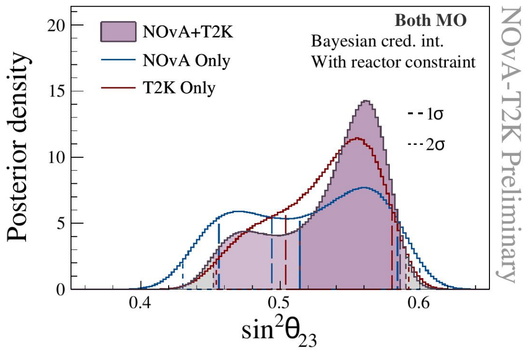
A joint fit between the two experiments has been performed.
All Results are preliminary.



T2K + NOvA Results

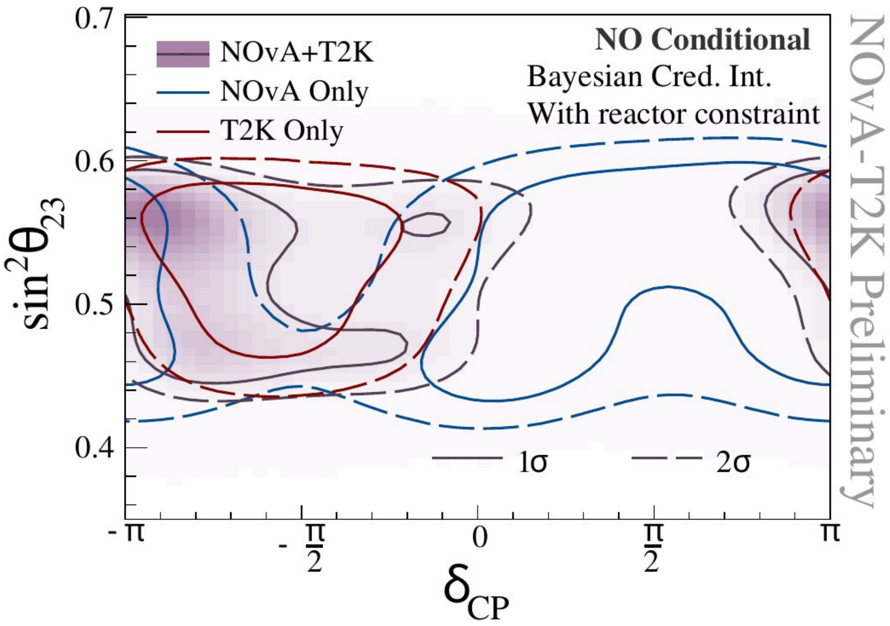


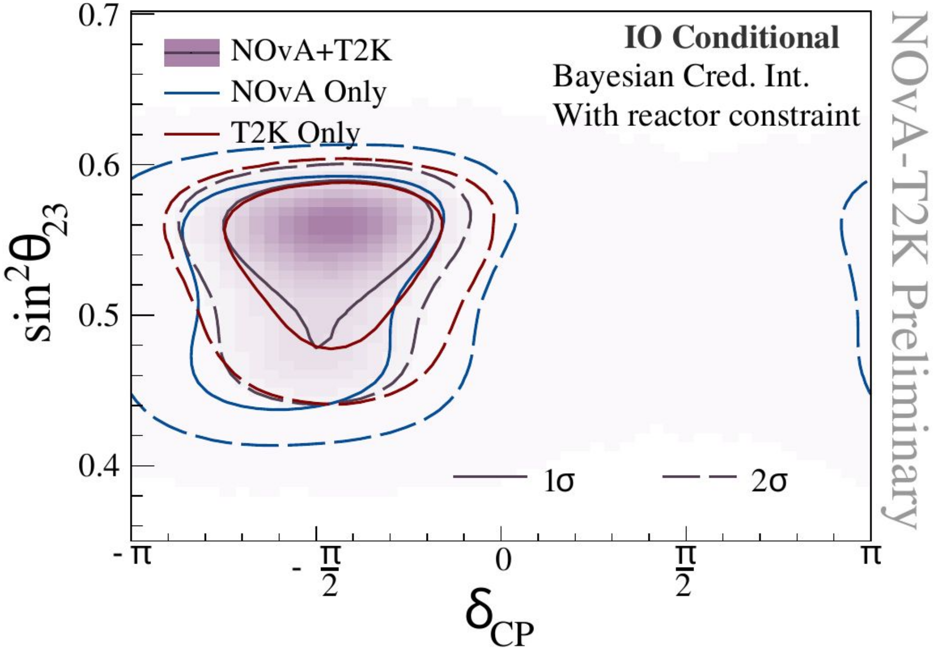




- Assuming inverted ordering gives 3σ sigma exclusion of CP-conserving values.
- Weak preference for inverted mass ordering
  (Also a weak preference for inverted ordering without the reactor constraint)
- Weak preference for upper θ_{23} octant
  (weak preference for lower octant without the reactor constraint)

T2K + NOvA Results





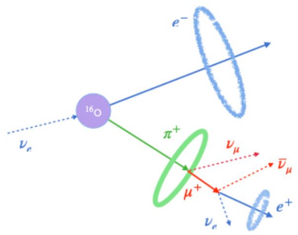
- The joint fit result is consistent with the separate T2K and NOvA results.
- In NO, the individual experiments preferred different phase-spaces, and the joint fit splits across this.
- In IO, where the experiments had good agreement, the joint fit tightents the constraint.

  → IO is preferred by the joint fit

The Future

The future: SK

- Expanded selection of ν_eCC1π by adding a multi-ring topology
- Addition of recent data, with increased Gd-loading
- Updates in simulation and treatment of systematics



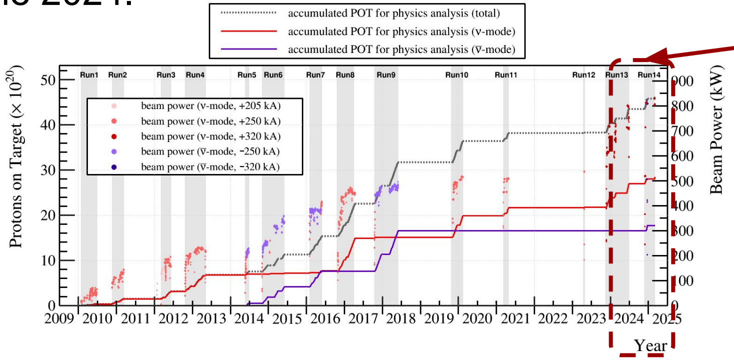
Multi-ring ν_e sample

The future: T2K Beam

Recent beam upgrades have been completed

- New Main Ring power supplies allowed repetition rate to be reduced from 2.48 s to 1.36s
- Horn current increased 250 kA → 320 kA to increase neutrino flux by ~10% with higher purity.
- Beam power reached above 800 kW in June 2024.

→ This data will be included in future analyses



New data to analyze!

The future: ND280 for the oscillation analysis

Upcoming developments to the existing/pre-upgrade ND280 oscillation analysis inputs.

- 4pi angular acceptance
- Anti-neutrino photon selection, neutron tagging
- New parameterisation for weighted detector systematics
- Improved cross-section model

T2K cross-section results

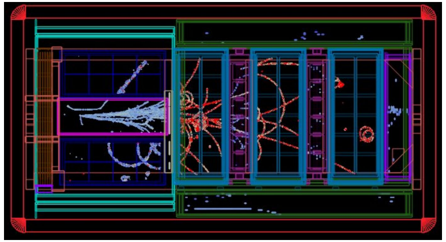
Recent cross-section measurements

- n-capture multiplicity in NCQE-like interactions on oxygen: Phys. Rev. D 112, 032003
- ν_e CCπ^+ on carbon arXiv:2505.00516
- NC1π^+ on carbon arXiv:2503.06849

→ See talk by Ellen Sandford: Latest neutrino cross-section results from T2K

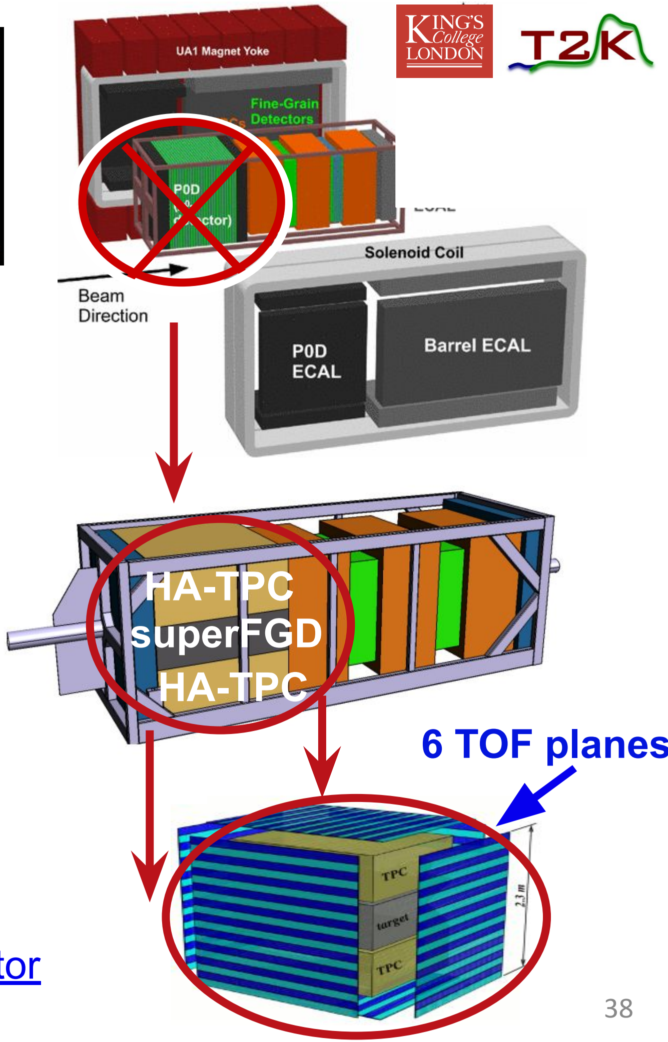
Wednesday, 10.10am Neutrino Physics session

Upgraded ND280



Part of the P0D detector replaced with:

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



The goal is for ND280 to reduce systematic errors in oscillation analyses in the search for δ_{CP} :

- Improved 4π acceptance for charged particles
- Reduce proton momentum threshold (~300 MeV/c)
- Neutron kinematics via time of flight
- Increased target mass for greater statistics

The Upgrade installation was completed in May 2024 and data is already being analysed!

Talk by Gioele Reina: First results from T2K's upgraded near detector

- Wed, 11am, Data Science and Detector R&D session

Summary

Summary

- **T2K Oscillation analysis** with additional SK data (10% more stats, and Gd loading)
  - CP conservation excluded at 90% C.L.
  - Weak preference for normal mass ordering and θ_{23} upper octant
- **T2K + SK joint analysis**
  - CP-conserving values of the Jarlskog invariant are excluded with a significance between 1.9σ and 2.0σ
  - First joint analysis, and and important step towards combined beam and atmospheric data analyses planned by next-generation neutrino oscillation experiments
- **T2K + NOvA**
  - Weak preference for inverted ordering, which is where the individual experiments had good agreement.
  - Assuming Inverted Ordering, gives 3σ sigma exclusion of CP-conserving values.
- **T2K Future**
  - New data from SK to be analysed, from the era of beam upgrades and increased Gd loading
  - The first physics results from the ND280 upgrade are in the pipeline!

BACKUP

T2K: Frequentist - w/ & w/o reactor constraint

Table 26: Best fit values for the OA23 analysis with reactor constraints, global best fit is in normal ordering

	Normal ordering	Inverted ordering
$\sin^2(\theta_{13})/10^{-3}$	$(21.9^{+0.9}_{-0.5})$	$(22.0^{+1.0}_{-0.4})$
δ_{CP}	$-2.08^{+1.33}_{-0.61}$	$-1.41^{+0.64}_{-0.82}$
Δm^2_{32} (NO)/Δm^2_{31} (IO)	$(2.521^{+0.037}_{-0.050})10^{-3}\mathrm{eV}^2/\mathrm{c}^4$	$(-2.486^{+0.043}_{-0.044})10^{-3}\mathrm{eV}^2/\mathrm{c}^4$
$\sin^2(\theta_{23})$	$0.568^{+0.024}_{-0.125}$ (90%)	$0.567^{+0.021}_{-0.048}$ (90%)
-2 ln L	649.06	651.013
-2 Δln L	0.	1.953

T2K Preliminary

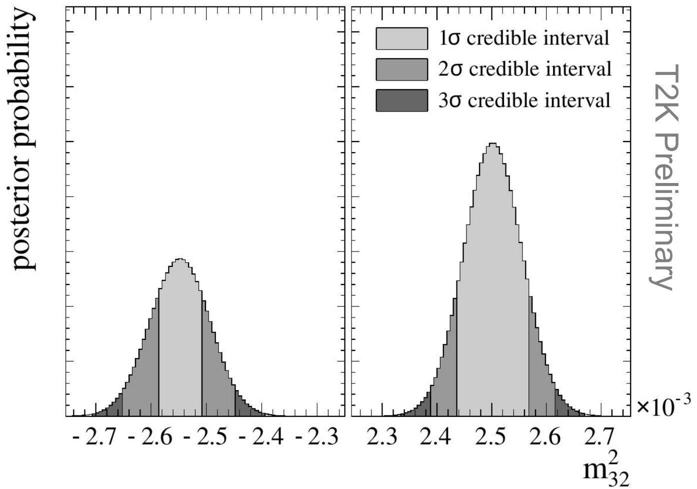
Table 27: Best fit values for the OA23 analysis **without** reactor constraints, global best fit is in normal ordering

	Normal ordering	Inverted ordering
$\sin^2(\theta_{13})/10^{-3}$	$(27.8^{+1.8}_{-6.9})$	$(31.0^{+1.8}_{-7.4})$
δ_{CP}	$-2.21^{+1.62}_{-0.75}$	$-1.29^{+0.63}_{-0.99}$
Δm^2_{32} (NO)/Δm^2_{31} (IO)	$(2.521^{+0.039}_{-0.050})10^{-3}\mathrm{eV}^2/\mathrm{c}^4$	$(-2.489^{+0.042}_{-0.046})10^{-3}\mathrm{eV}^2/\mathrm{c}^4$
$\sin^2(\theta_{23})$	$0.458^{+0.130}_{-0.021}$ (90%)	$0.458^{+0.127}_{-0.021}$ (90%)
-2 ln L	648.837	649.655
-2 Δln L	0.	0.818

T2K Preliminary

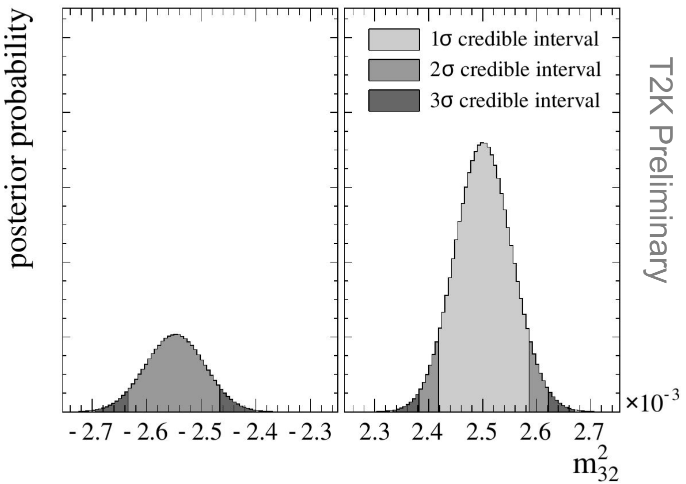
T2K: Δm^2_{32} Bayesian w/ & w/o reactor constraints

Without reactor constraint



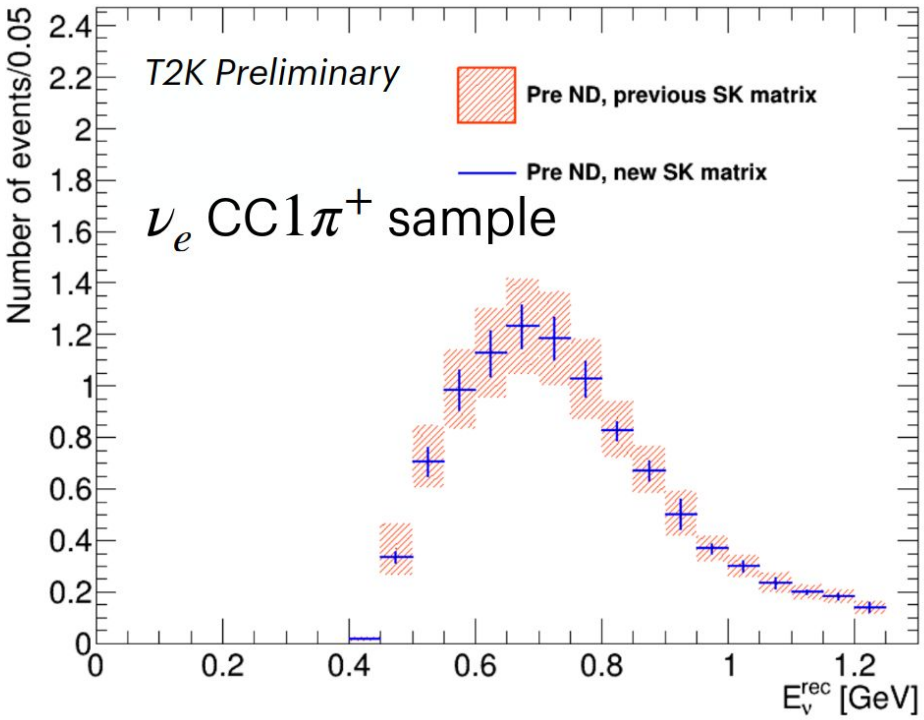
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.27	0.37	0.63
IH ($\Delta m^2_{32} < 0$)	0.17	0.20	0.37
Sum	0.43	0.57	1.000

With reactor constraint



	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IH ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00

Effect of improvements to SK detector systematic treatment



T2K Oscillation Analysis Fake Data Studies

- **Axial form factor**
  - Reweights using z-exp parameterization
  - Reweights using 3-comp parameterization

- **Nuclear models**
  - SF
  - LFG
  - CRPA

- **Removal energy model**

- **Pion model**
  - Model parameter variations
  - Different model (Martini)

- **Effect of adding radiative corrections**

- **Data driven reweights based on ND data**

T2K + NOvA Results