DE LA RECHERCHE À L'INDUSTRIE

Neutrino Oscillation Results From the T2K Experiment

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On behalf of the T2K Collaboration

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Overview

- Neutrino Oscillations
- The T2K Experiment
- Oscillation Analysis Strategy
- Oscillation Parameters Measurements
- Future Plans
- Summary & Outlook

NEUTRINO OSCILLATIONS PHYSICS

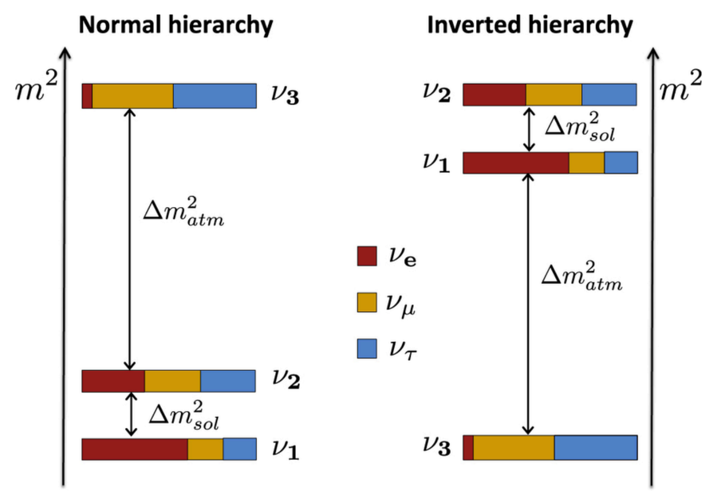
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12}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

Atmospheric and accelerator
$\theta_{23} \sim 50°$
$|\Delta m_{32}^2| \sim 2.5\text{x}10^{-3}\ \text{eV}^2$

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

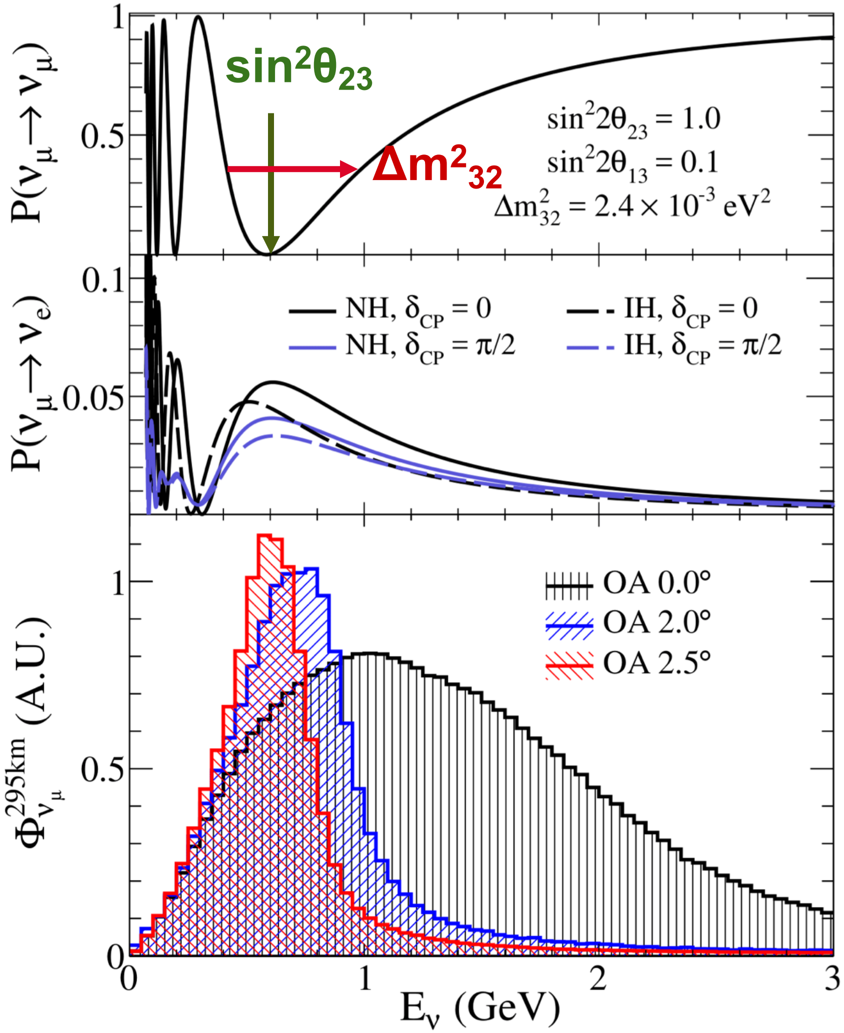
Solar and reactor
$\theta_{12} \sim 34°$
$\Delta m_{12}^2 \sim 7.5\text{x}10^{-5}\ \text{eV}^2$

- What's keeping long-baseline neutrino oscillation physicists up at night:
  - CP VIOLATION PHASE δ_{CP}
  - θ_{23} OCTANT
  - MASS ORDERING
  - CONSISTENCY OF THE WHOLE PMNS FRAMEWORK



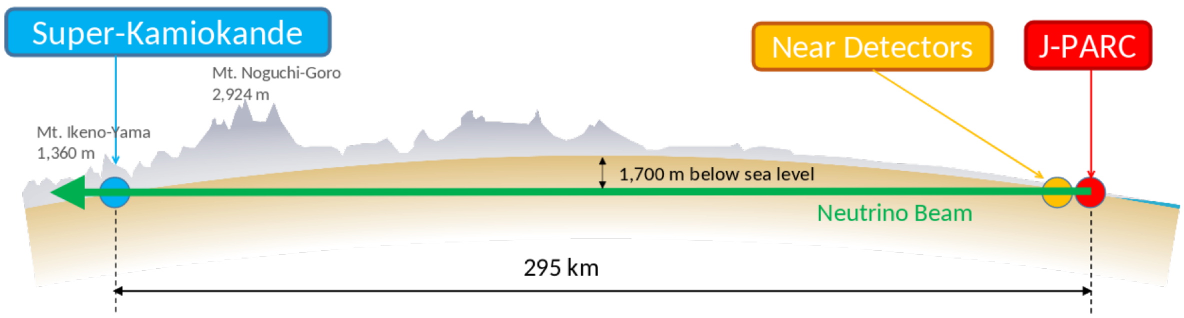
HOW WE MEASURE OSCILLATION PARAMETERS

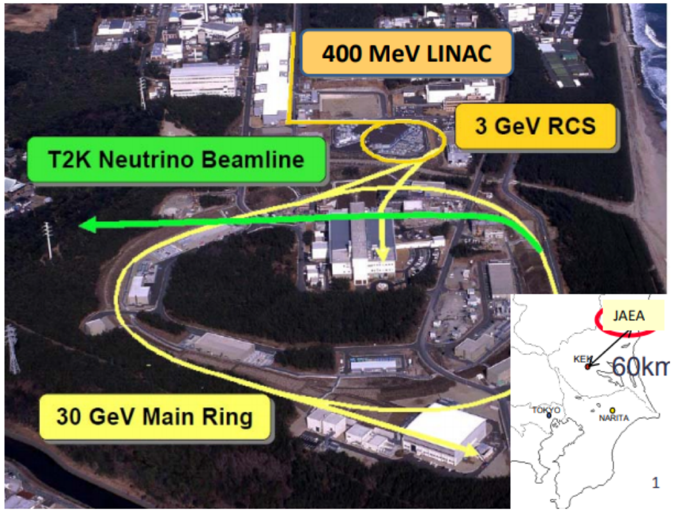
Phys.Rev.D 88 (2013) 3, 032002

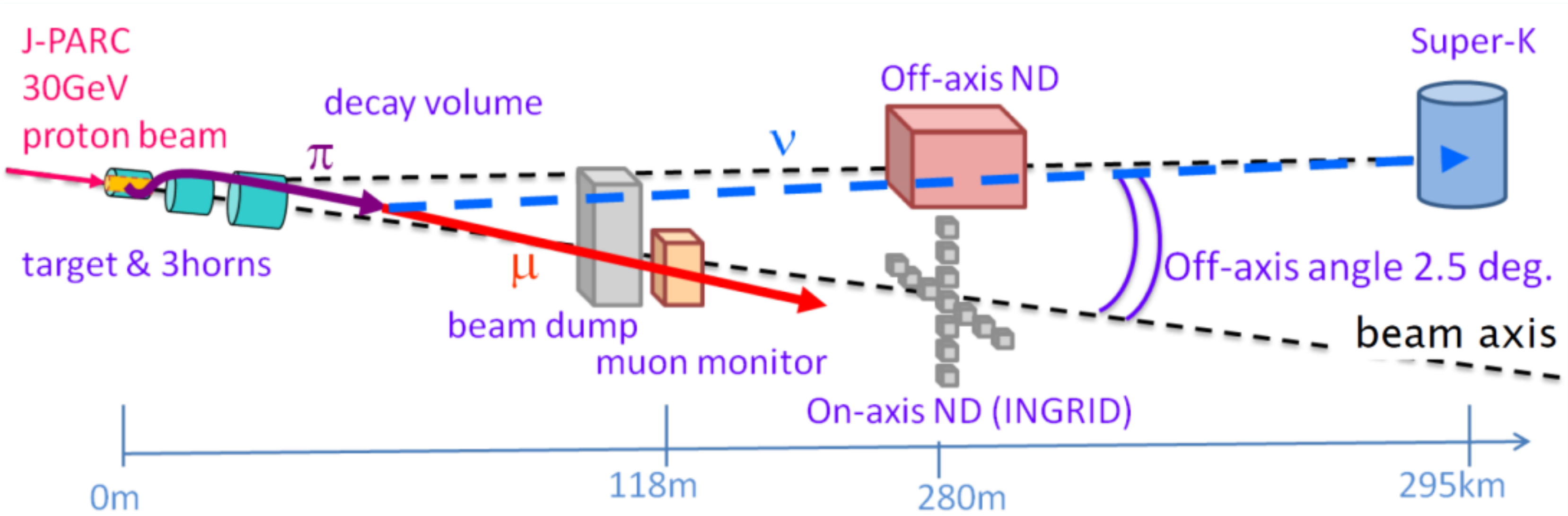


- Measure ν_μ disappearance and ν_e appearance
- Maximum oscillation probability is at **600 MeV** for T2K baseline (295 km)
- Use **off-axis effect** to obtain narrow flux distribution at 600 MeV and reduce ν_e contamination
- $\boldsymbol{\delta_{CP}}$ inferred from ν_e/anti-ν_e appearance asymmetry
- Matter effects give **small dependence on mass hierarchy (10%)**

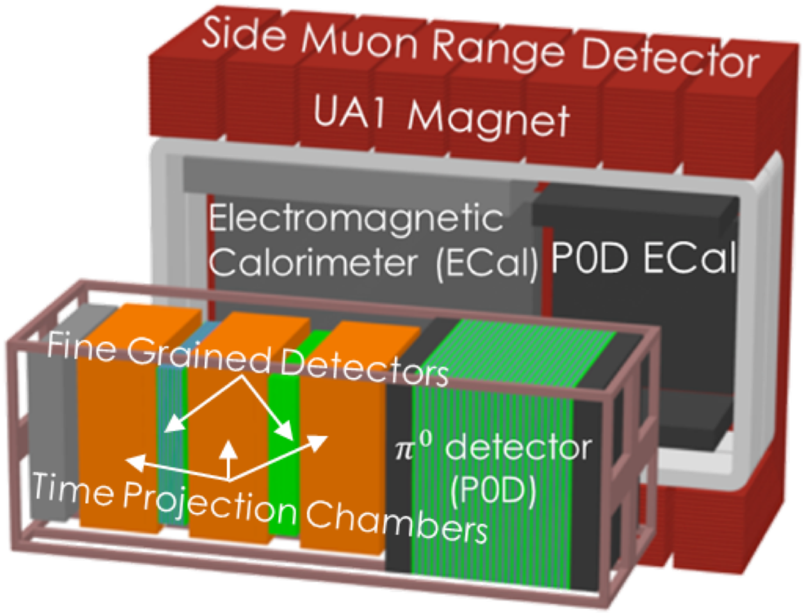
THE T2K EXPERIMENT







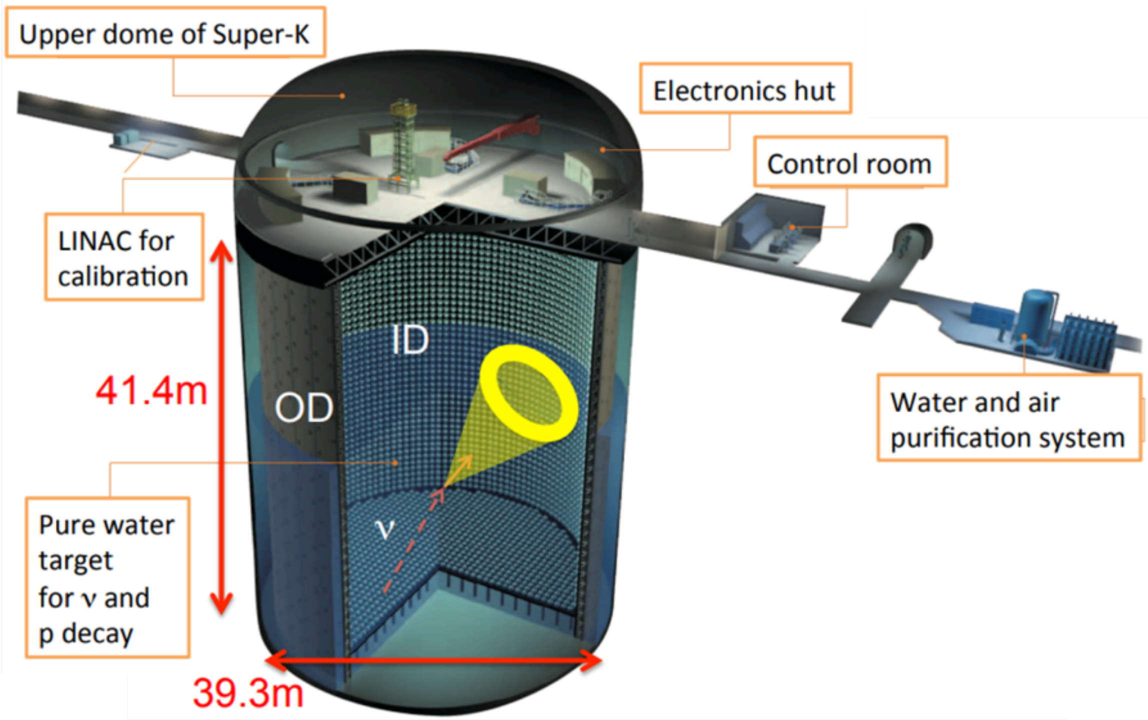
Near Detector at 280 m (ND280)

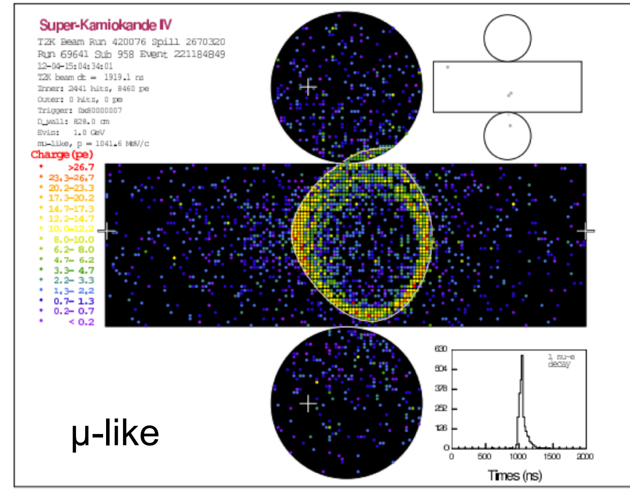


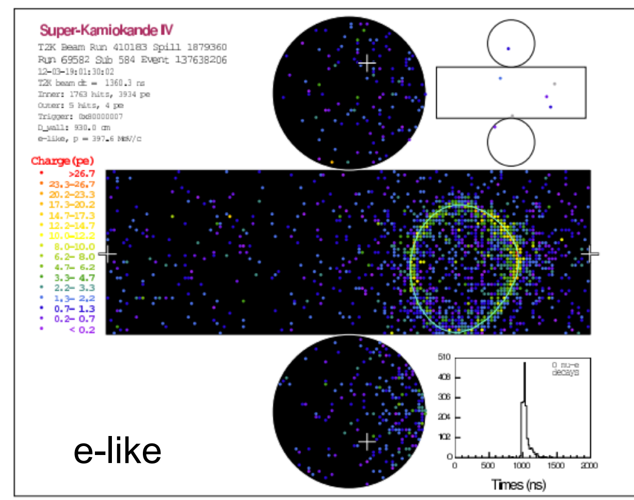
- Two fine grained scintillating detectors - FGD1 (C) and FGD2 (C,O)
- 3 Time Projection Chambers (TPCs)
- One Upstream π^0 detector
- Surrounded by ECal and UA1 magnet
- **2.5^o off-axis**
- Constrains flux and cross-section systematics in **oscillation analysis**

Our near detectors are also used for exotic searches and cross-section measurements (see Ka Ming Tsui's talk!)

SuperKamiokande (Far Detector)

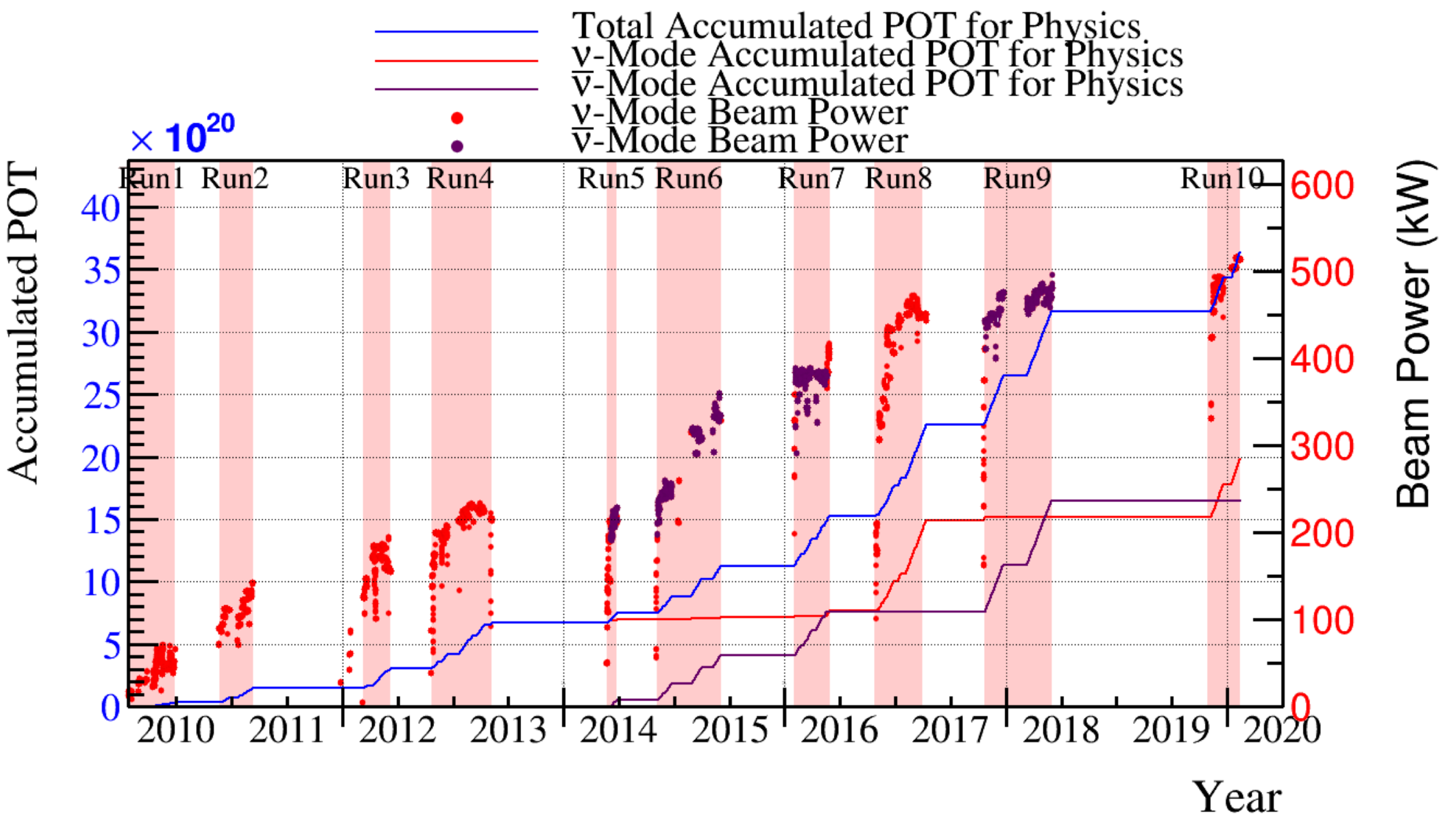






- 1000 m under the Mount. Ikeno
- 50 kton of pure water
- 22.5 kton of fiducial mass
- ~11,100 inner detector (ID) PMTs (20'')
- 1,885 outer detector (OD) PMTs (8'')
- direction/e-μ ID based on Cherenkov ring pattern

DATA TAKING STATUS SINCE 2009

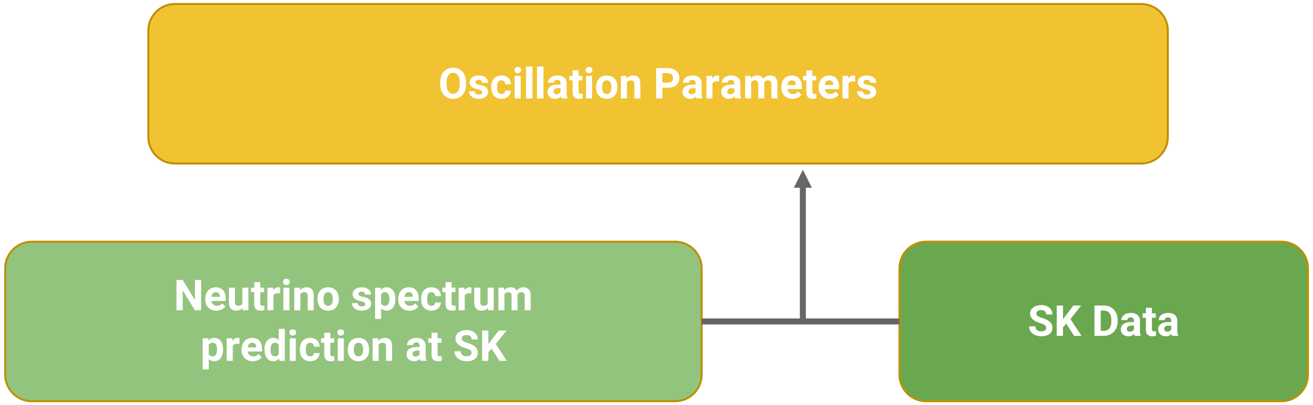


*POT = Protons On Target

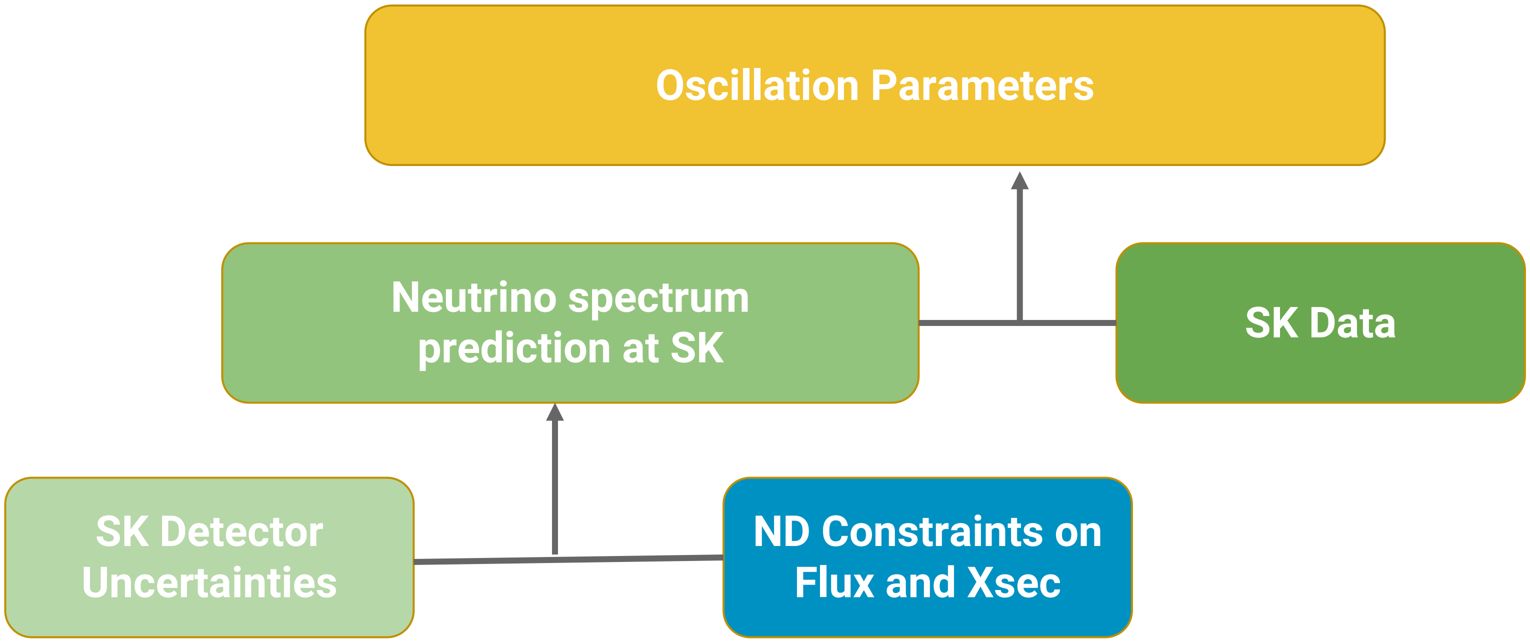
- This year we've reached **515 kW** stable operation beam power
- We now have a total of **1.97×10^{21} POT** in ν mode and **1.63×10^{21} POT** in anti-ν mode.

Oscillation Parameters

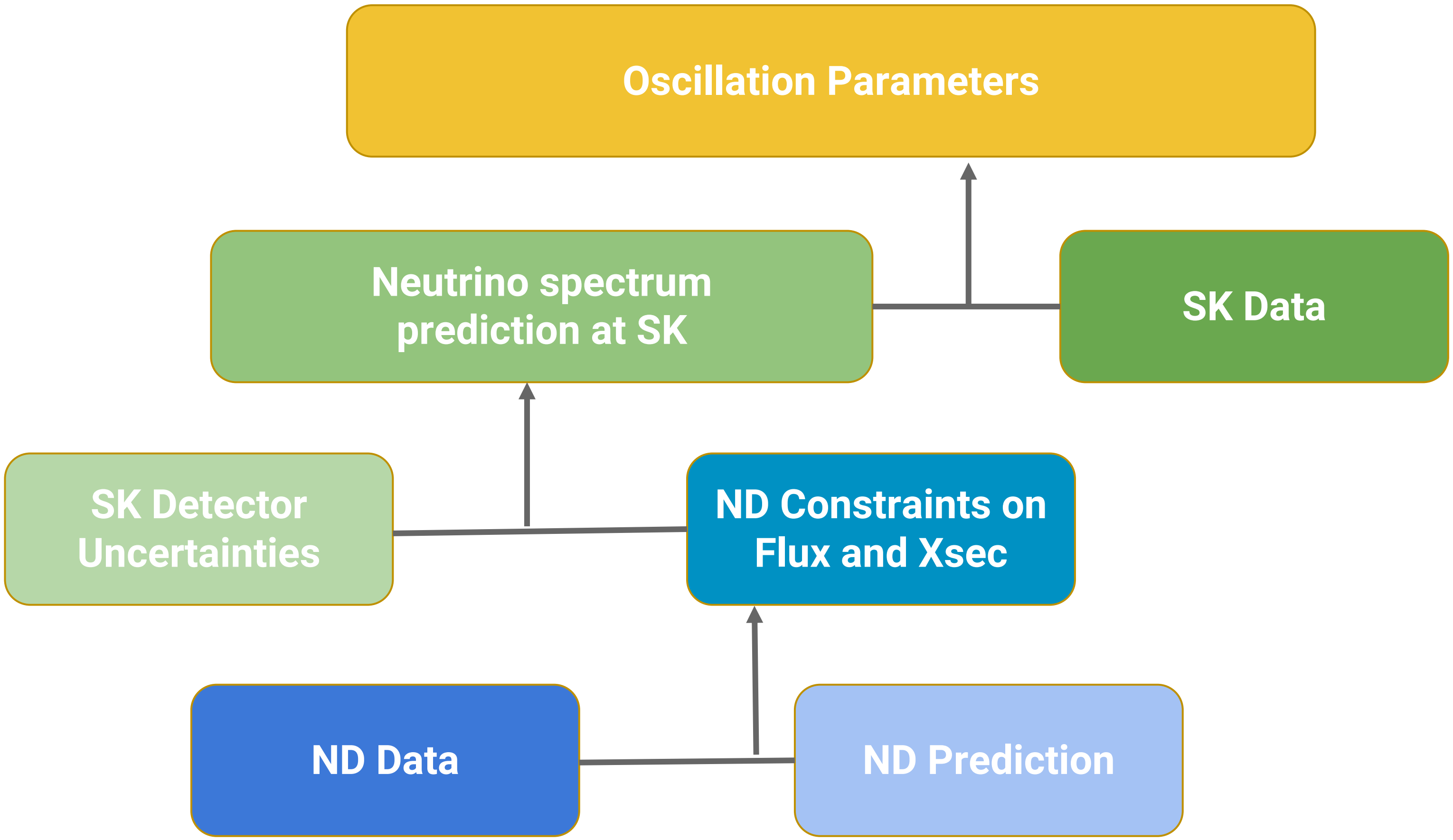
Oscillation Analysis Strategy

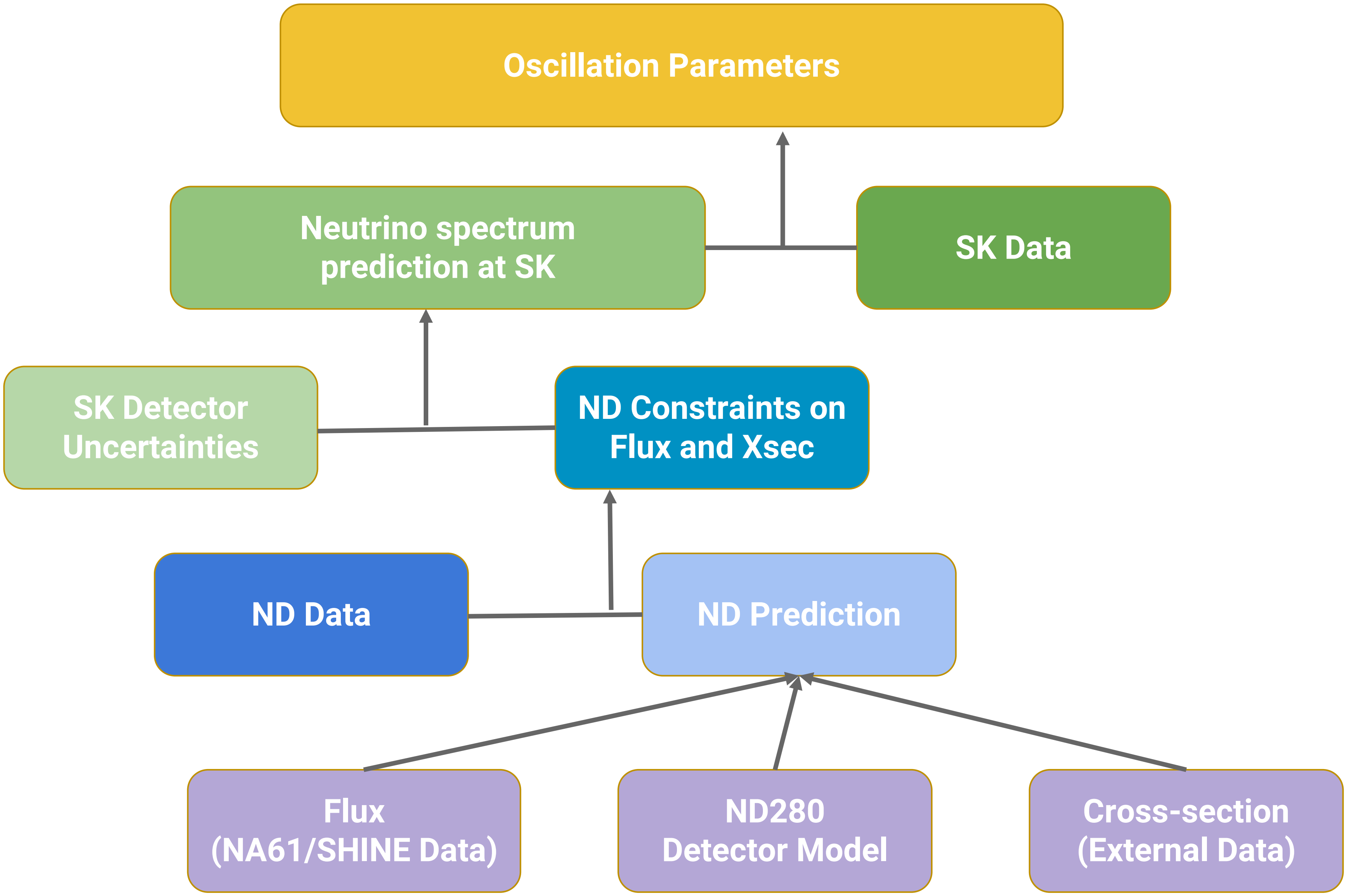


Oscillation Analysis Strategy

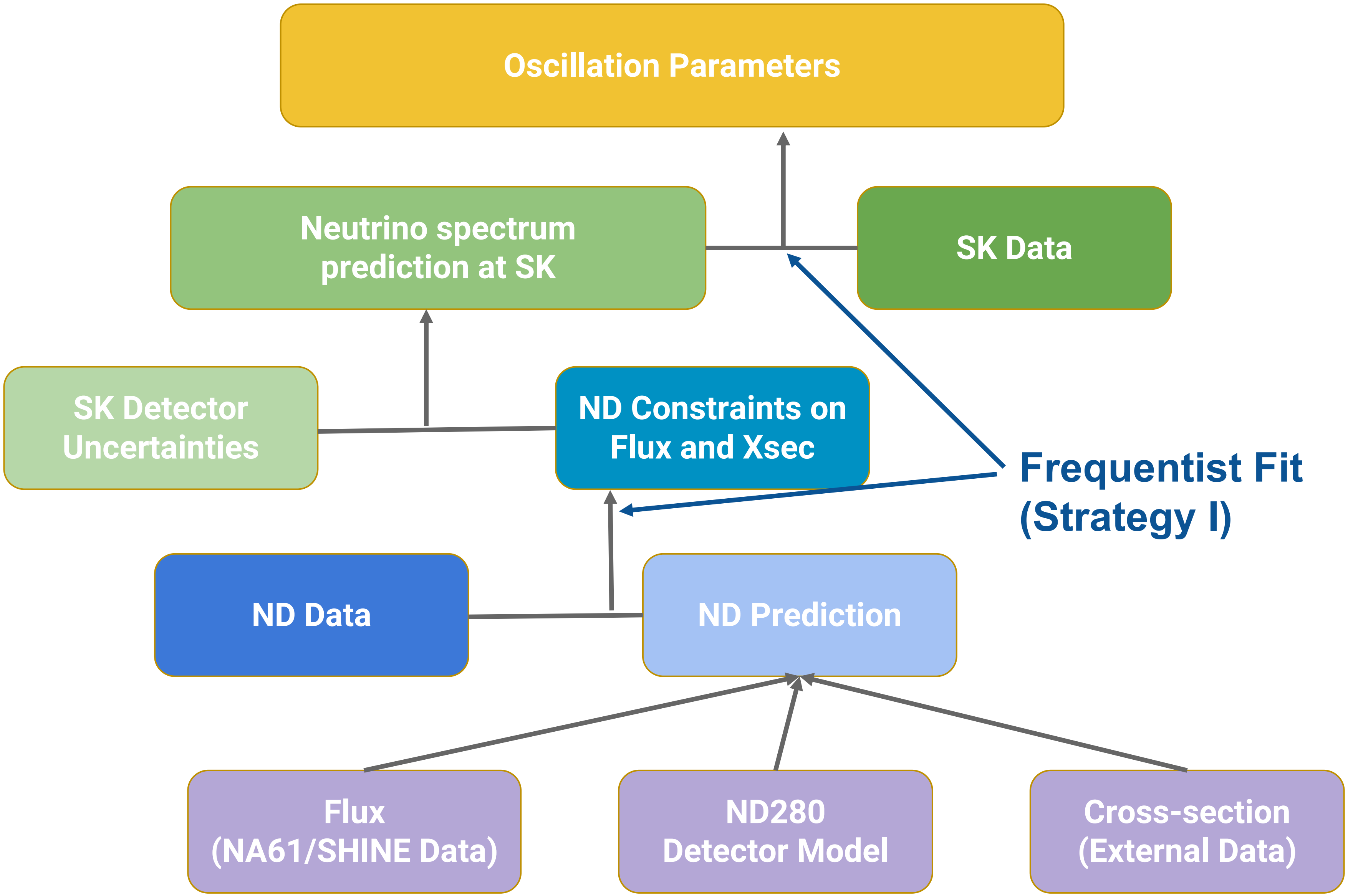


Oscillation Analysis Strategy

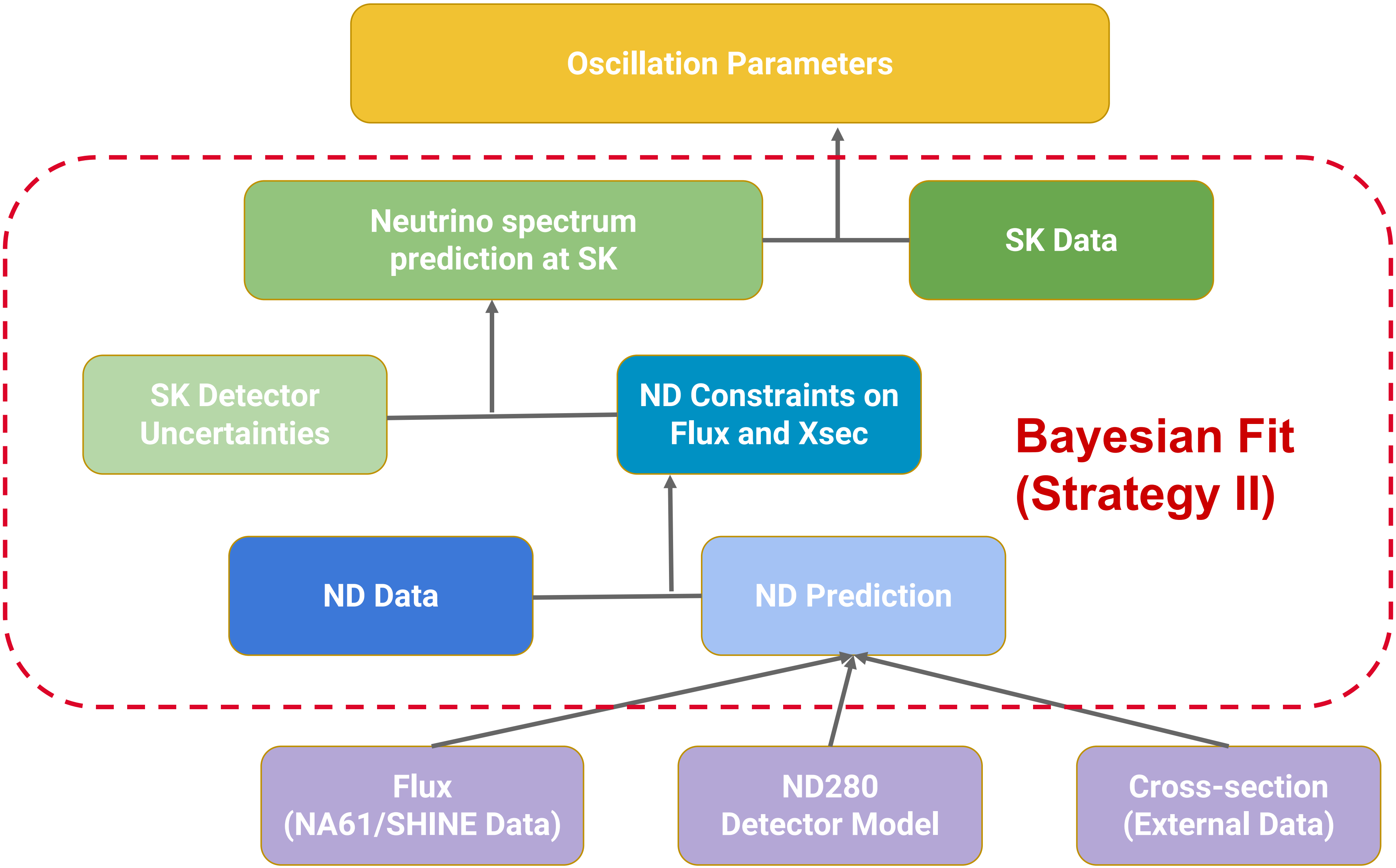



Oscillation Parameters
Neutrino spectrum prediction at SK
SK Data
SK Detector Uncertainties
ND Constraints on Flux and Xsec
ND Data
ND Prediction
Flux (NA61/SHINE Data)
ND280 Detector Model
Cross-section (External Data)

Oscillation Analysis Strategy

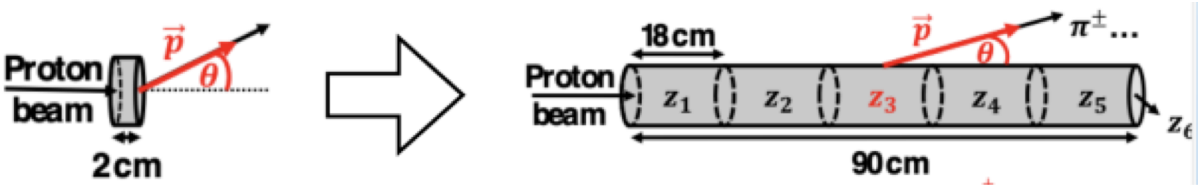


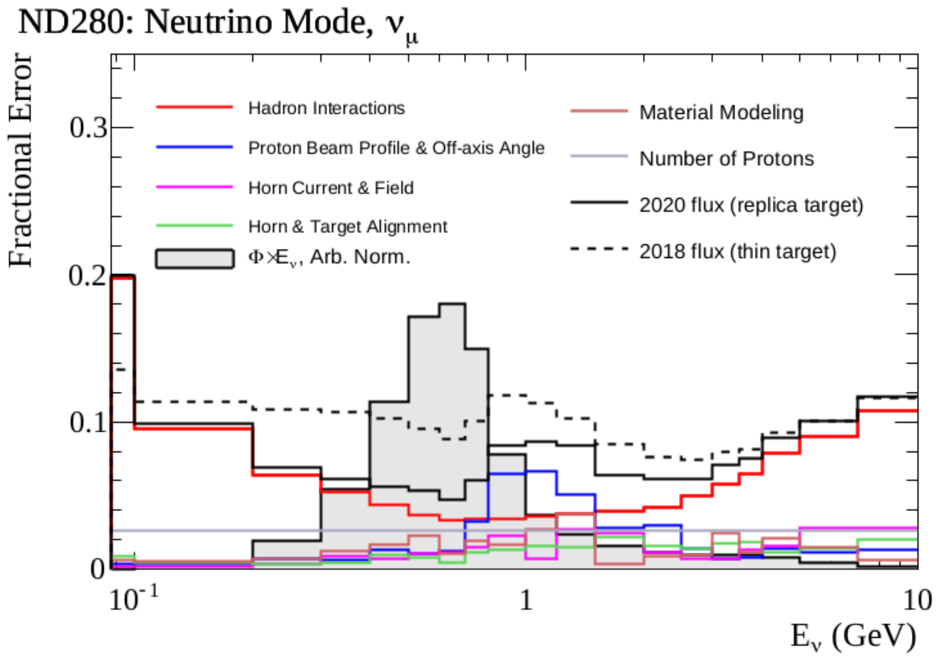
Oscillation Analysis Strategy



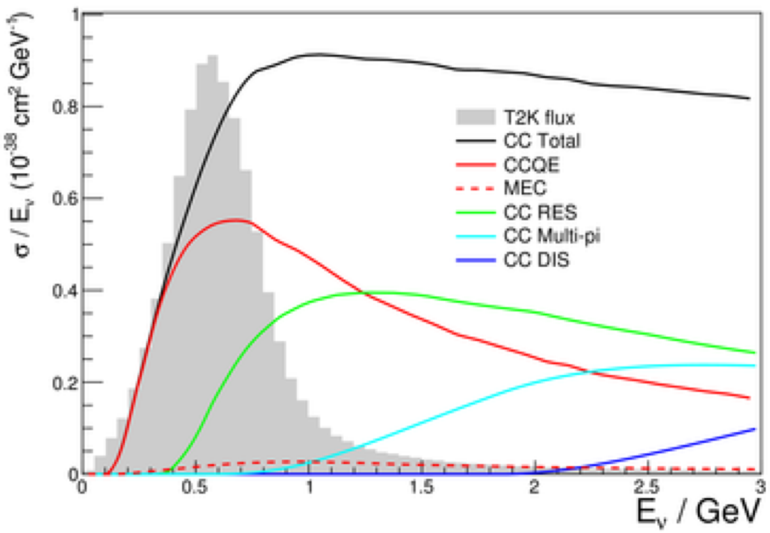
Flux Uncertainties

- Primary interactions are simulated with FLUKA and then reweighted to **NA61/SHINE (external hadron production experiment at CERN)** data
- Previously: NA61/SHINE data was obtained with a thin graphite target. New this year: we use NA61/SHINE data obtained with a full T2K **replica target**.
- Flux uncertainties reduced from **~8% to 5%**



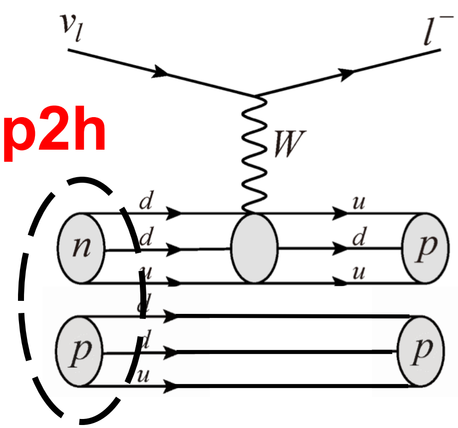


ND280 Samples

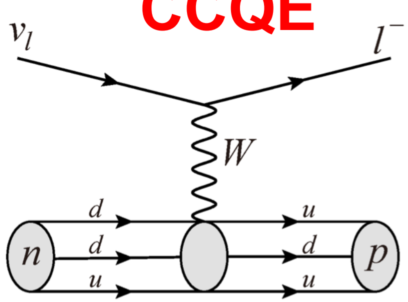


- Three dominant scattering processes at T2K energies: CCQE (and 2p2h), RES, DIS

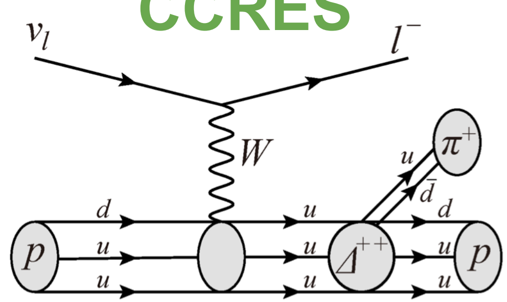
2p2h



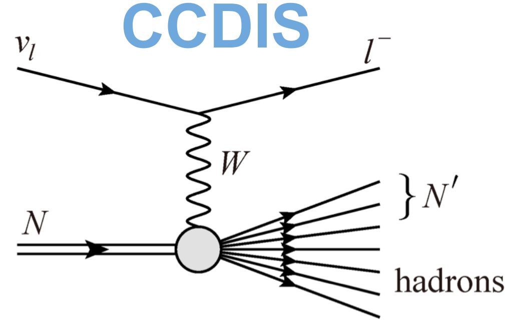
CCQE



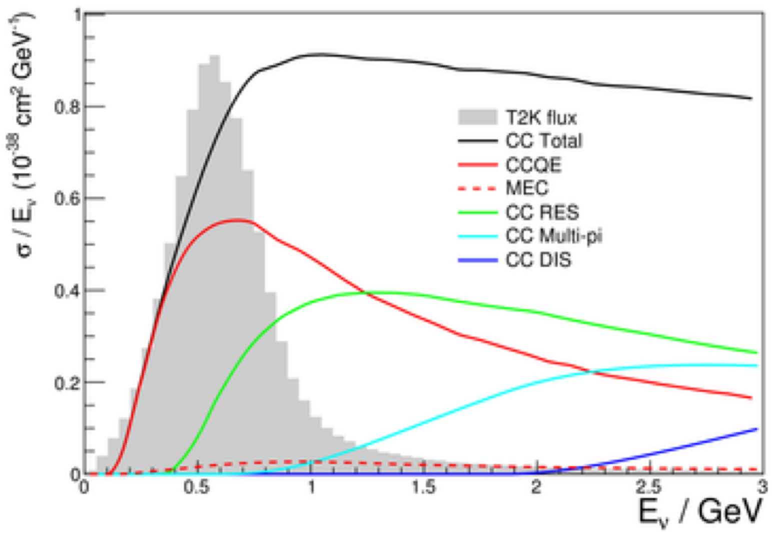
CCRES



CCDIS

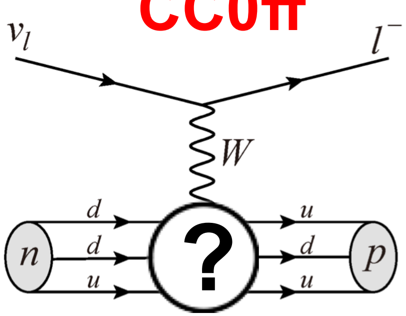


ND280 Samples

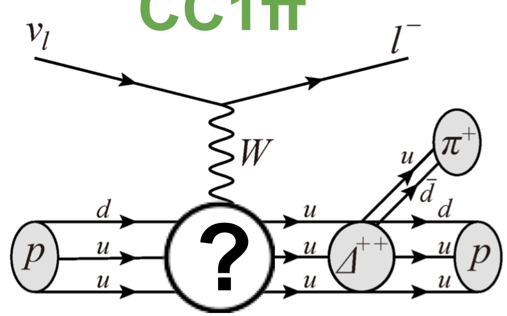


- Three dominant scattering processes at T2K energies: CCQE (and 2p2h), RES, DIS
- Define samples enriched in each of these processes using **reconstructed pion multiplicity**

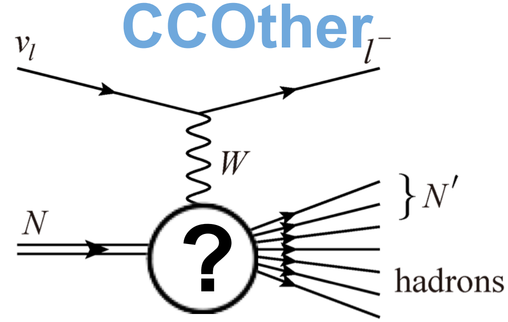
CC0π



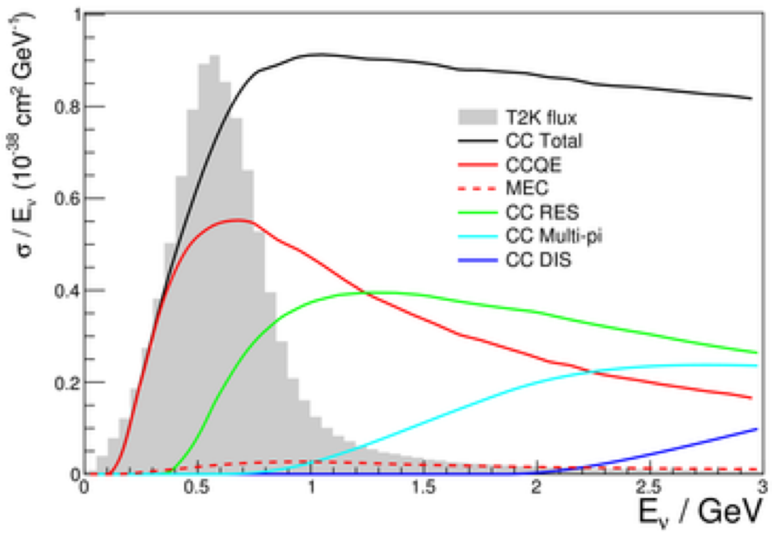
CC1π



CCOther

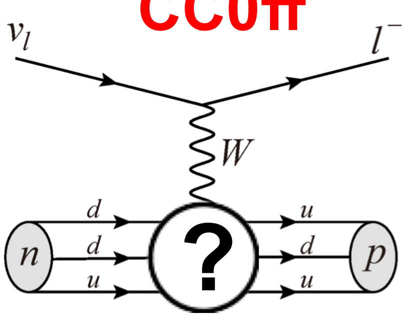


ND280 Samples

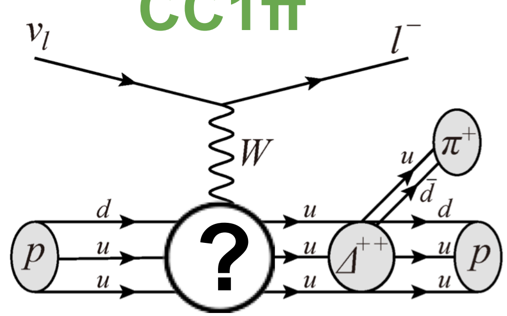


- Three dominant scattering processes at T2K energies: CCQE (and 2p2h), RES, DIS
- Define samples enriched in each of these processes using **reconstructed pion multiplicity**
- Samples divided between FGD1 (C) and FGD2 (C,O) and neutrino-antineutrino beam modes
- Also **wrong sign sample** (neutrino background in antineutrino beam mode)

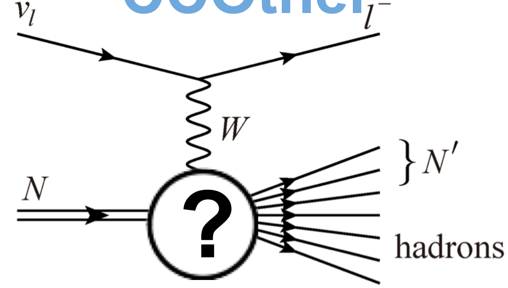
CC0π



CC1π



CCOther

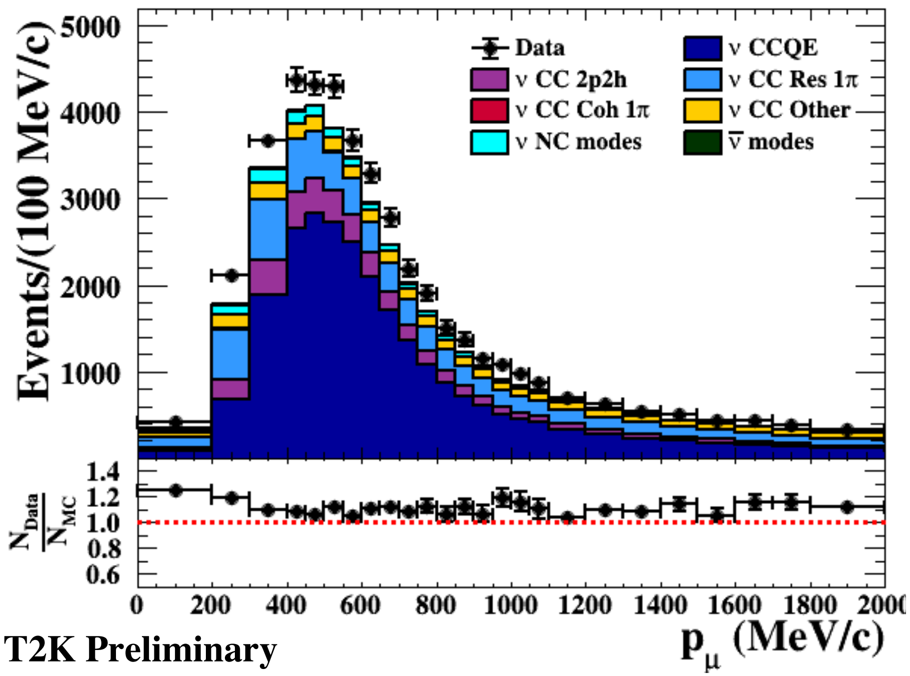


CROSS-SECTION MODEL

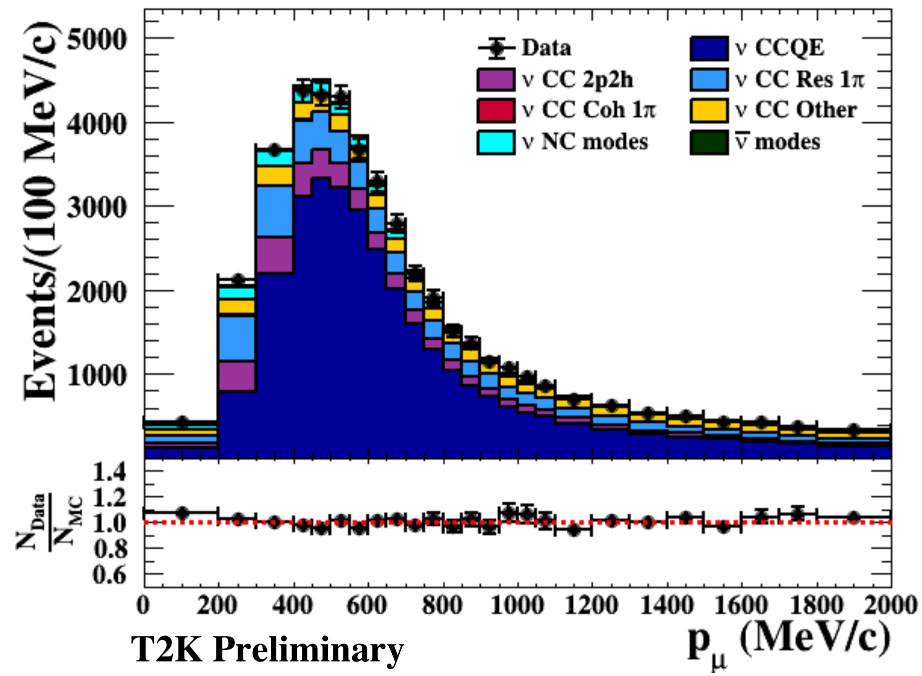
- Baseline nuclear model: moved from Relativistic Fermi Gas + RPA (2018) to a **tuned Benhar Spectral Function**.
- **2p2h**: new uncertainty on **energy dependance** of the cross-section
- **Removal energy** (energy to extract a bound nucleon): much smaller uncertainty due to constraints from electron scattering data.
- **Correlated pion FSI errors** between near and far detector
- **Improved** multi-pi and DIS treatment

The Near Detector Fit

- Our model of cross-section and flux has good flexibility to reproduce well the data (ND fit **p-value of 74%**)

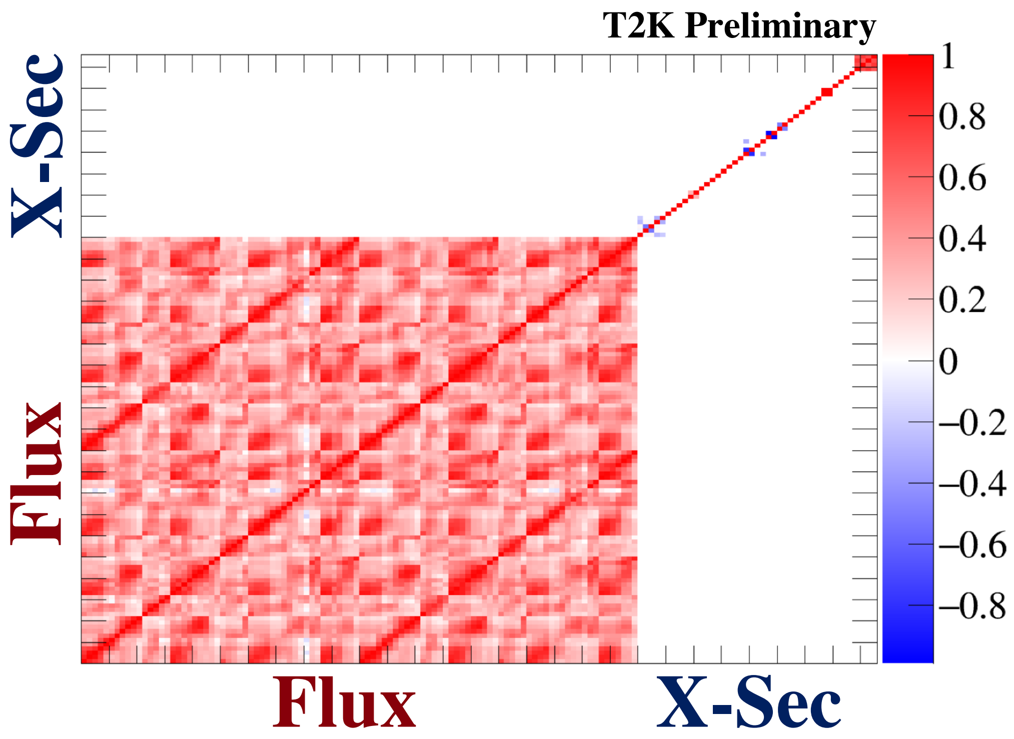


Prefit



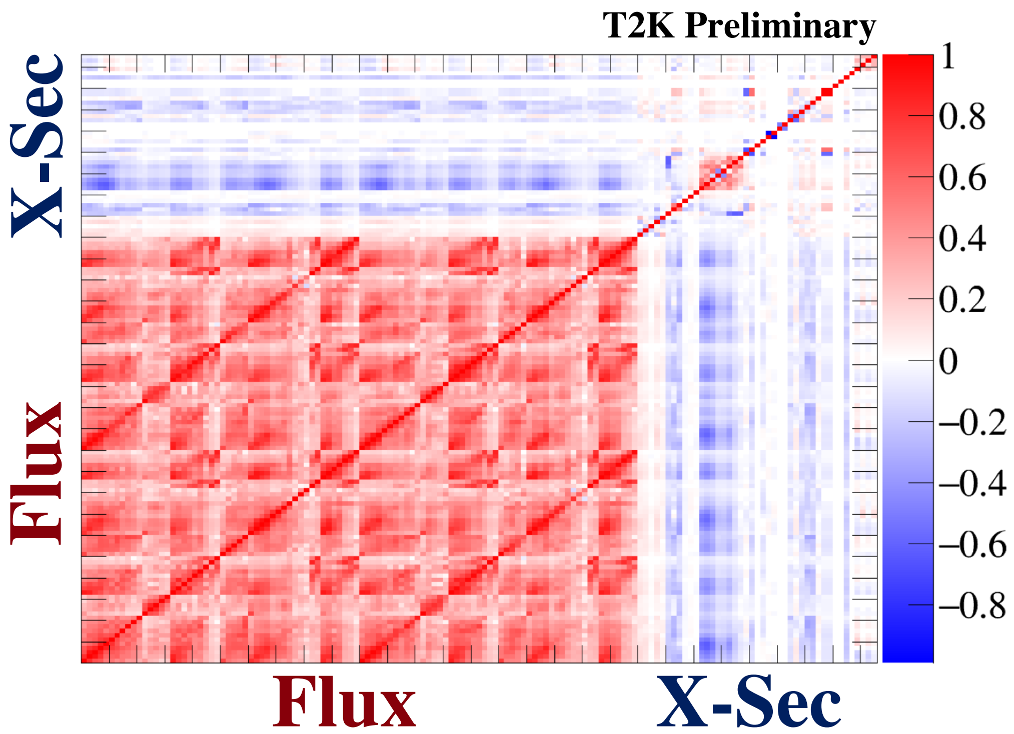
Postfit

- Before the fit there are no correlations between the flux and the cross-section parameters



The Near Detector Fit

- Before the fit there are no correlations between the flux and the cross-section parameters
- Near detector fit introduces (anti)correlations between flux and cross-section parameters



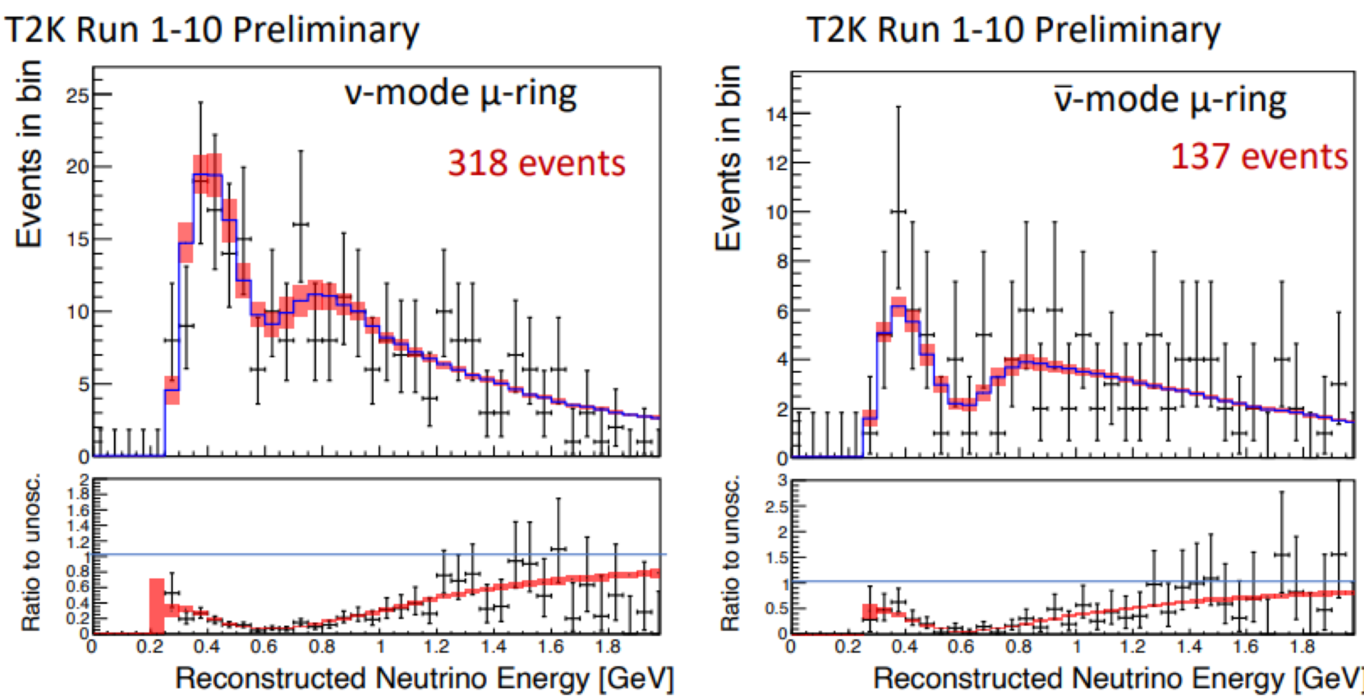
The Near Detector Fit

- Before the fit there are no correlations between the flux and the cross-section parameters
- Near detector fit introduces (anti)correlations between flux and cross-section parameters
- Lower prefit uncertainties from **~13% to ~4%** at far detector

Sample	FHC 1Rμ	RHC 1Rμ	FHC 1Re	RHC 1Re	FHC 1Re1de
Flux+Cross section (before ND)	11.1%	11.3%	13.0%	12.1%	18.7%
Flux+Cross section **(after ND)**	**3.0%**	**4.0%**	**4.7%**	**5.9%**	**14.3%**

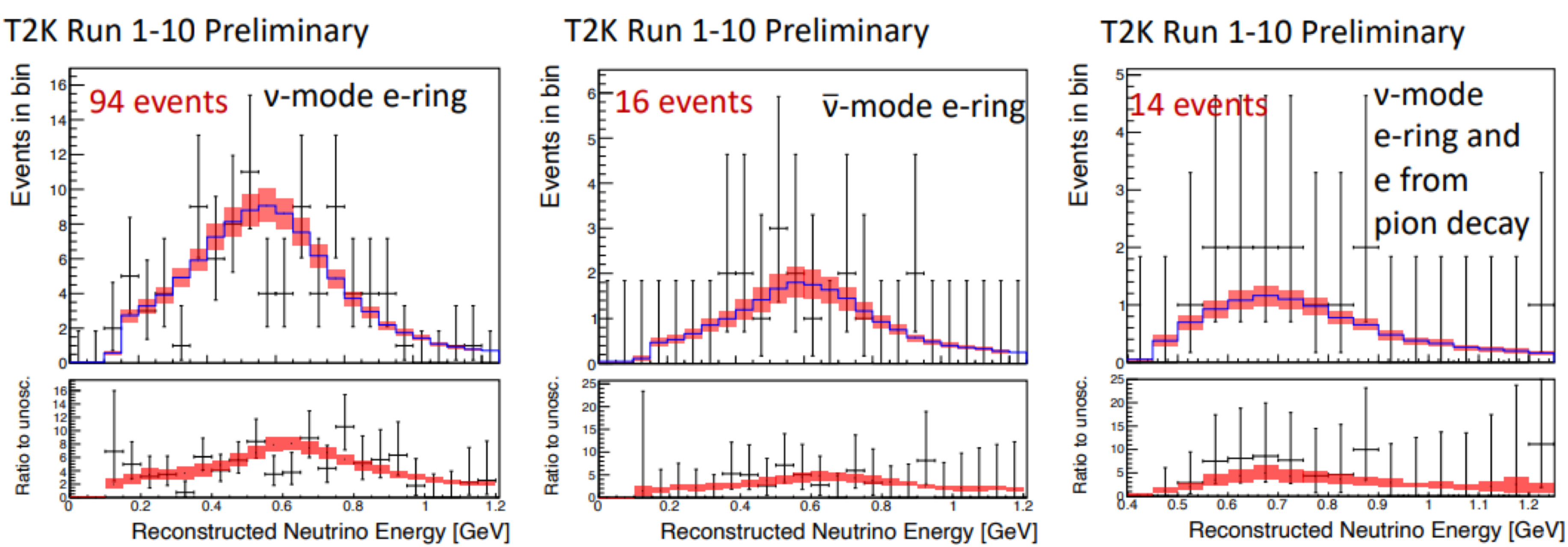
SK Samples and Data

- Five samples at SK, single ring selections based on lepton flavour
- **Red bands: systematic uncertainties**
- 1 ring μ samples (dominated by CC0π events)

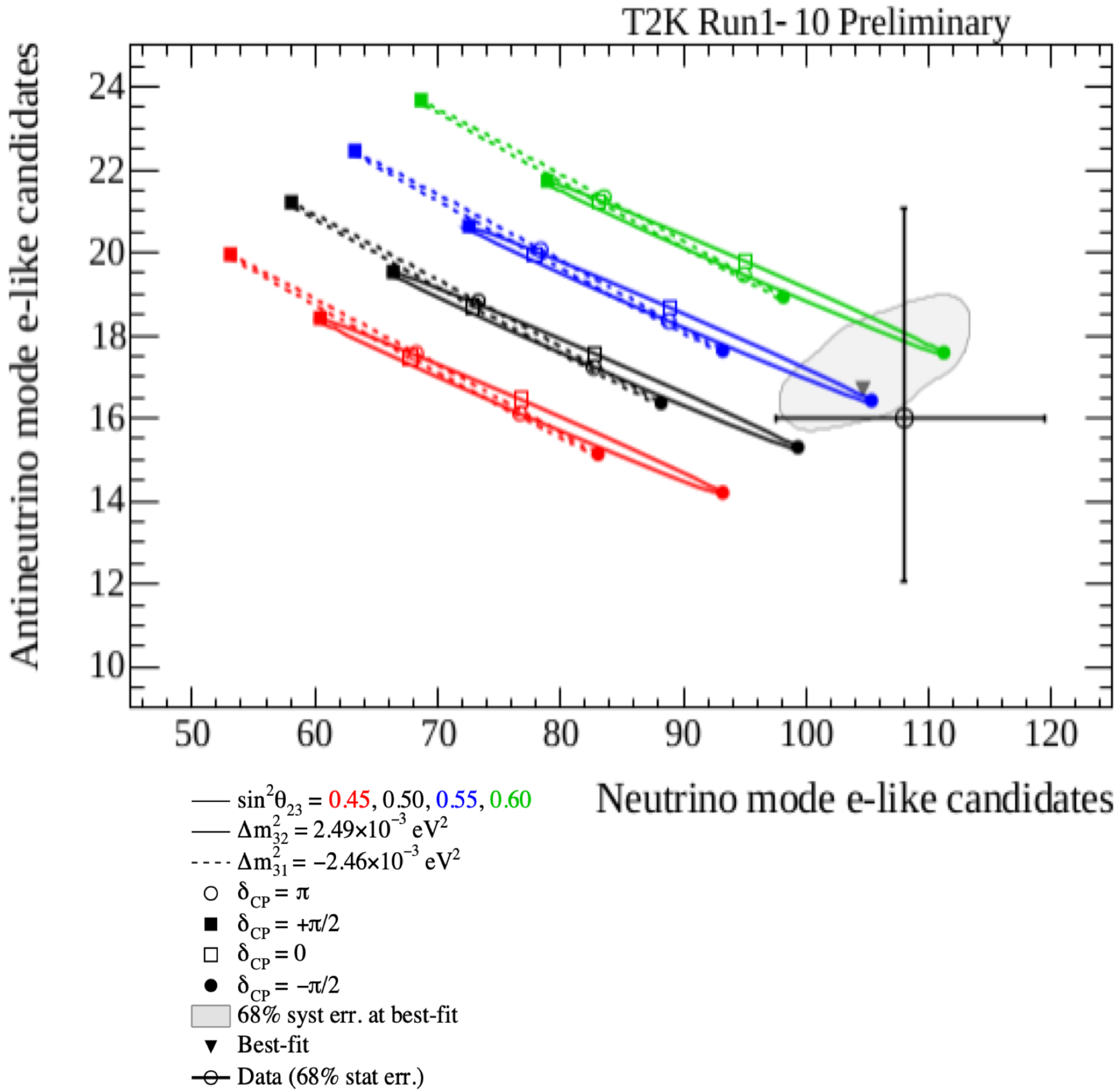


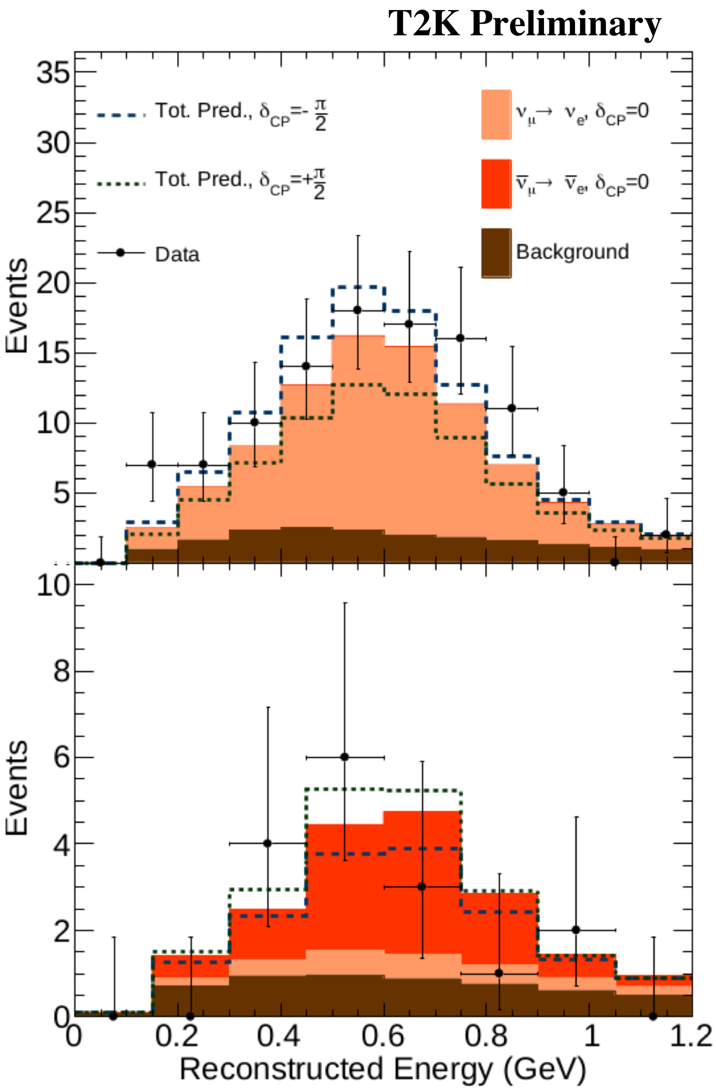
SK Samples and Data

- Five samples at SK, based on the lepton flavour and the ring multiplicity
- **Red bands: systematic uncertainties**
- Uncertainties on electron-like samples 4.7% in neutrino mode, 5.9% in antineutrino mode and **14.3%** in Michel electron sample
- 1-ring-electron (enriched in CC0π events) and 1-ring-e-1-Michel-electron (enriched in CC1pi events) -> larger systematic errors



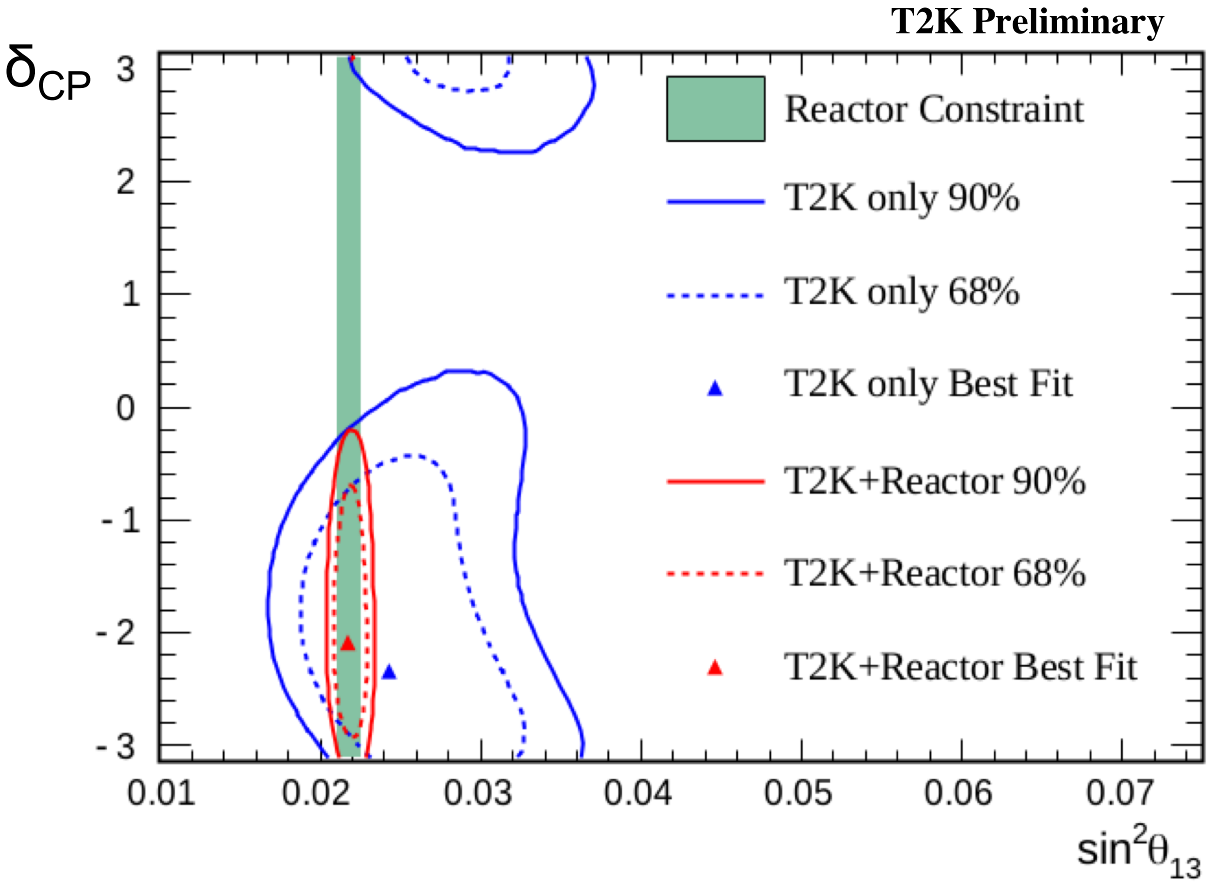
Appearance Results





δ_{CP} VS Θ_{13} AND REACTOR CONSTRAINT

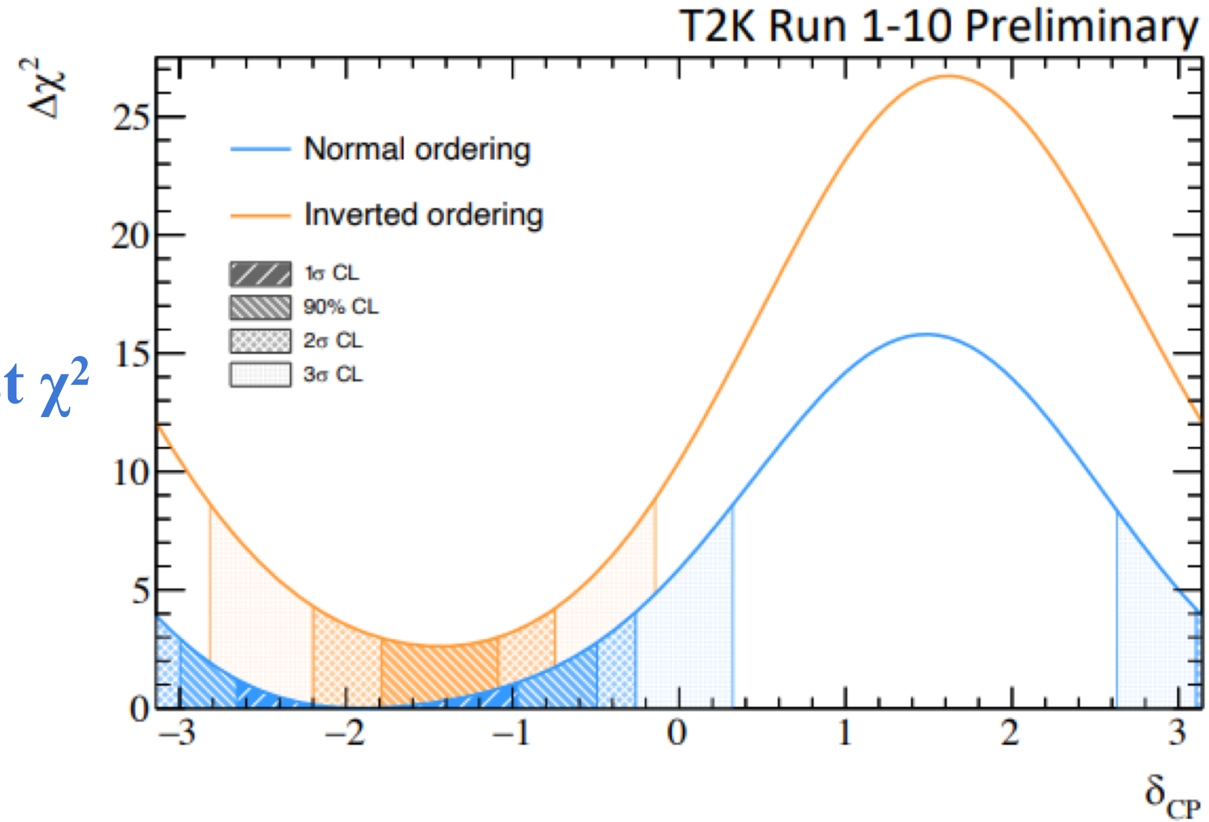
- T2K contours for θ_{13} are fully compatible (better than 1σ) with PDG2019 value - all the other results shown in this talk are shown with this reactor constraint applied



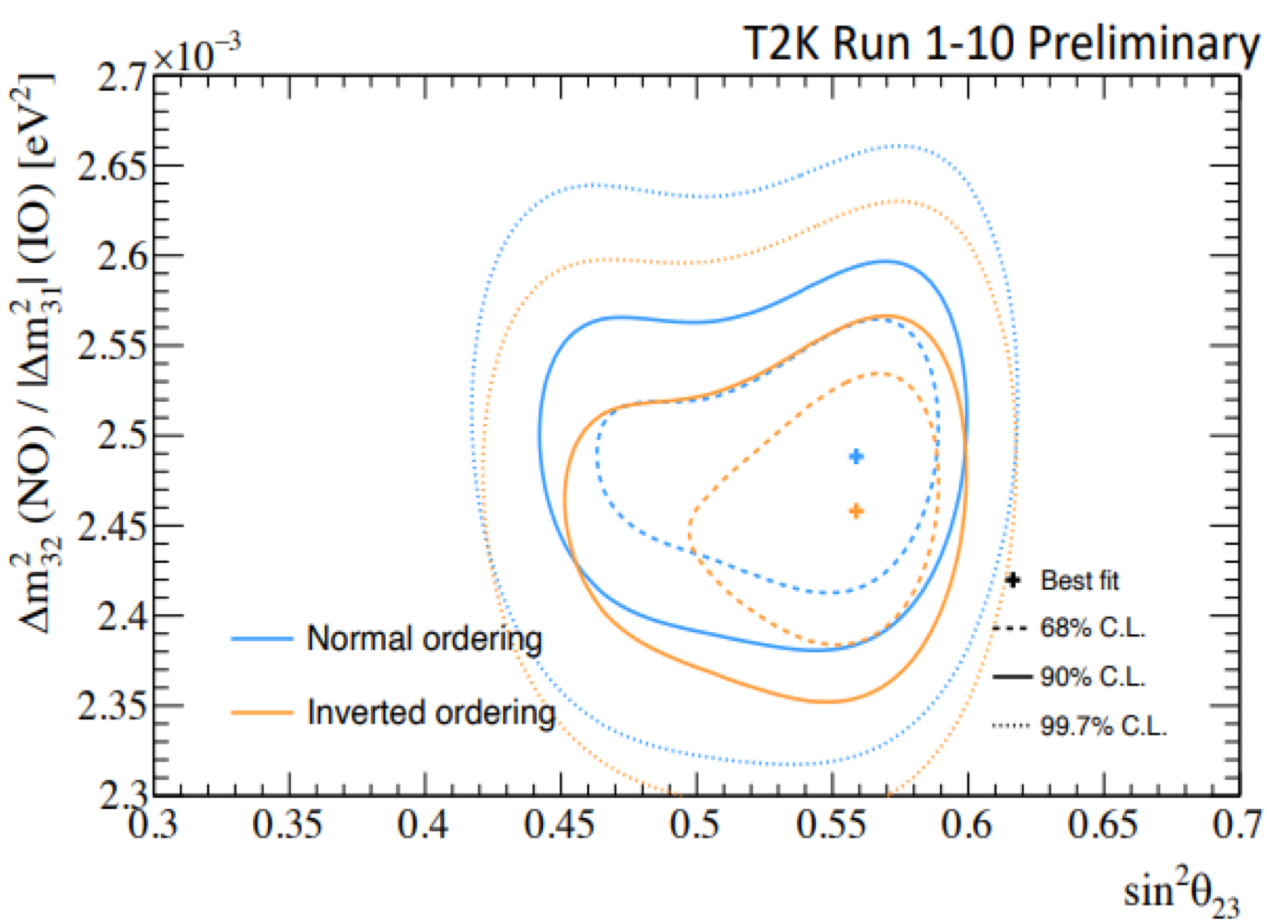
δ_{CP} INTERVALS (1D)

- δ_{CP} CP violating values are preferred
- Quantitatively: we exclude 35% of all δ_{CP} values at 3σ
- CP conserving values $(0,\pi)$ excluded at 90% CL
- Small preference for NH

Frequentist χ^2

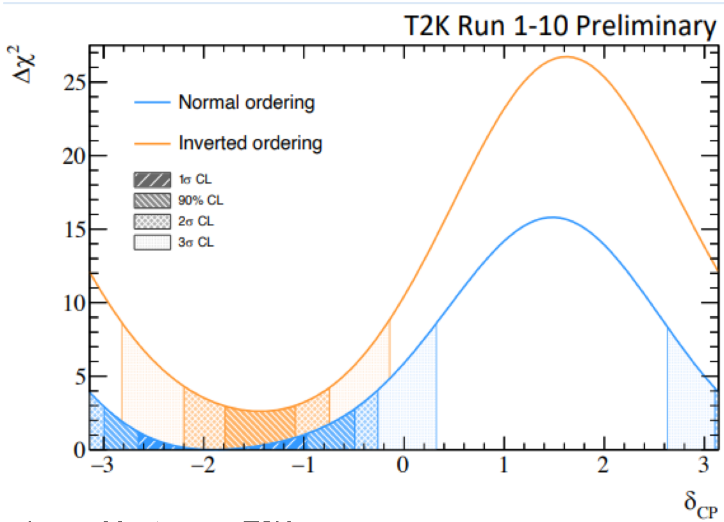


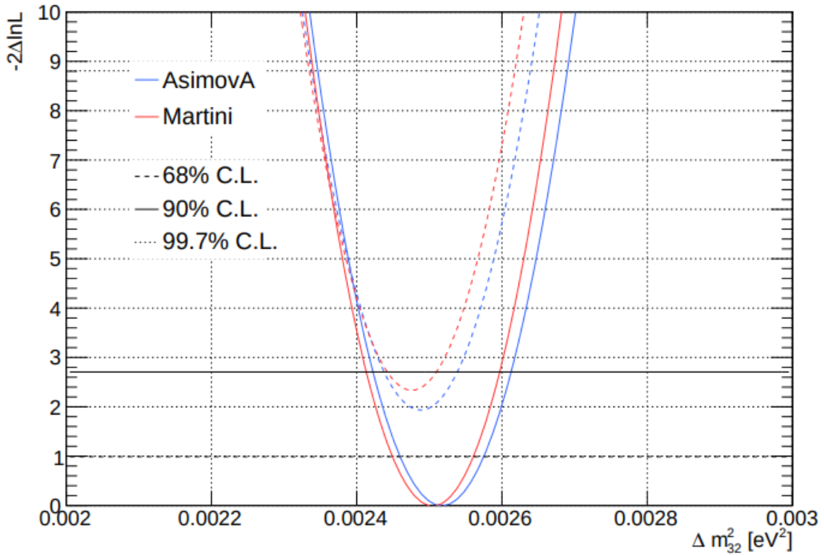
- Slight preference for upper octant



How could this go wrong?

- We know our models or fitting procedure aren't perfect or foolproof
- **Test the robustness** using alternative models, tunes or educated guesses
  - e.g.: alternative 2p2h models; ND280 or external data-driven tunes.
- After the robustness studies we performed, the largest impact we saw was a **small bias of 1.4x10^{-5} on Δm^2_{32}** which we've added as an additional uncertainty
- The effect of including the largest uncertainty from the robustness studies on the δ_{CP} intervals is to move them by **0.073 to the left** and **0.080 to the right**.





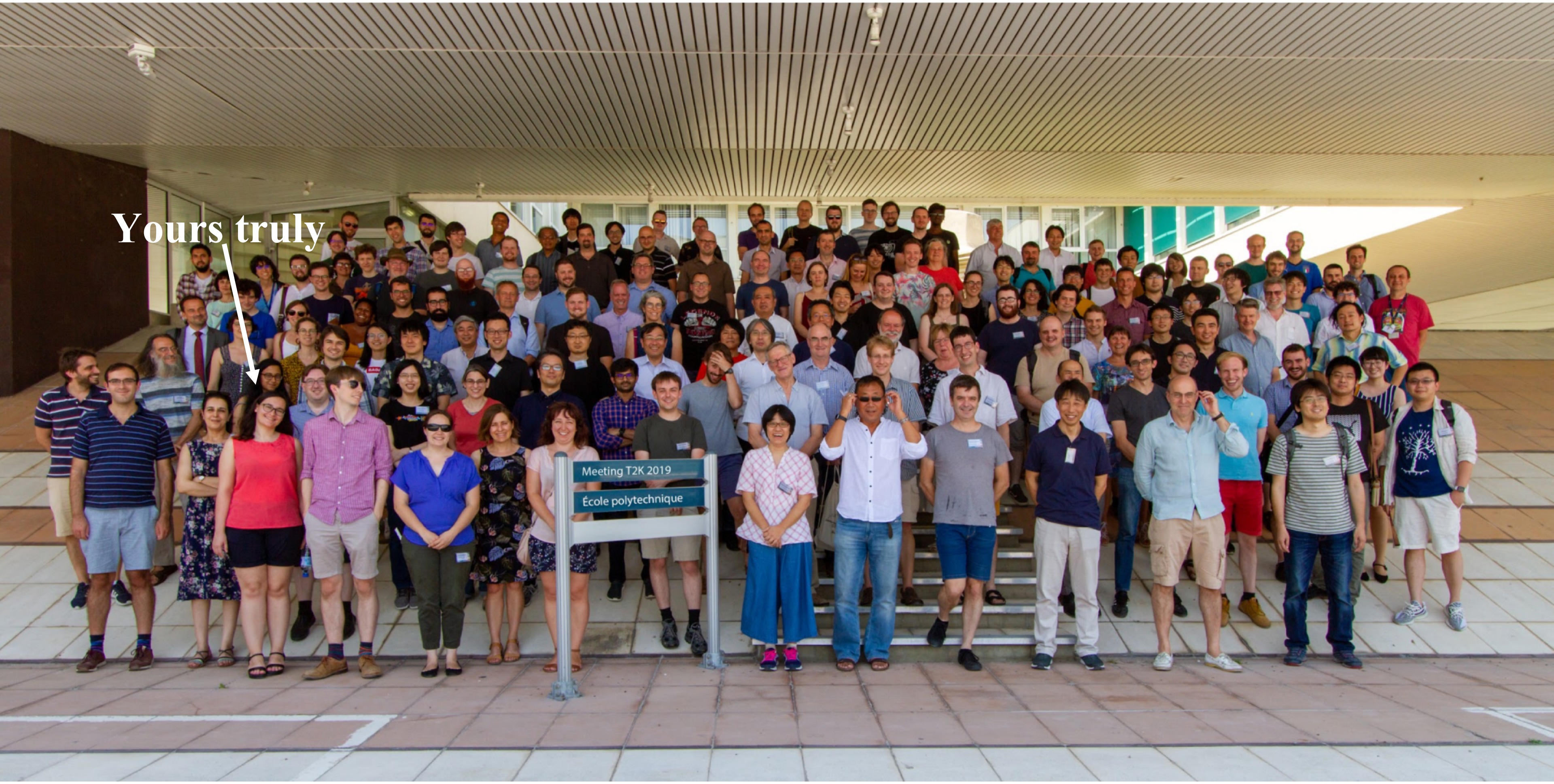
WHAT'S NEXT?

- J-PARC Main Ring Upgrade for High Intensity Neutrino Beam
  - Now operating stably at 515kW - target is **1 MW**
- Near Detector Upgrade - see Davide Sgalaberna's talk
- SK Gd loading -> **enhance neutron detection**
- **New and improved selections** are being included at both ND280 and SK for the next analysis
- Joint fits
  - **T2K-SK** atmospherics
  - **T2K-NOvA** - see next talk on new NOvA results
  - Combining different neutrino data sets and energies helps lift degeneracies and reach better sensitivity

Summary

- The new results obtained by T2K **exclude 35% of δ_{CP} values at the 3σ level**
- Slight preference for **upper octant of θ_{23} and normal hierarchy**
- Many improvements in this analysis
  - nearly **twice as much data** as in the previous analysis at the **near detector**
  - **33% more data** at the far detector in neutrino mode
  - NA61/SHINE **replica target** flux tune
  - **huge improvements** in systematic treatment of **cross-section uncertainties** within the fitting framework (in particular, moving to a Spectral Function nuclear model and improved description of removal energy systematics)
  - generally **improved** fitter framework
- Exciting future plans
  - **ND280 Upgrade**
  - **Joint Fits**

T2K Collaboration

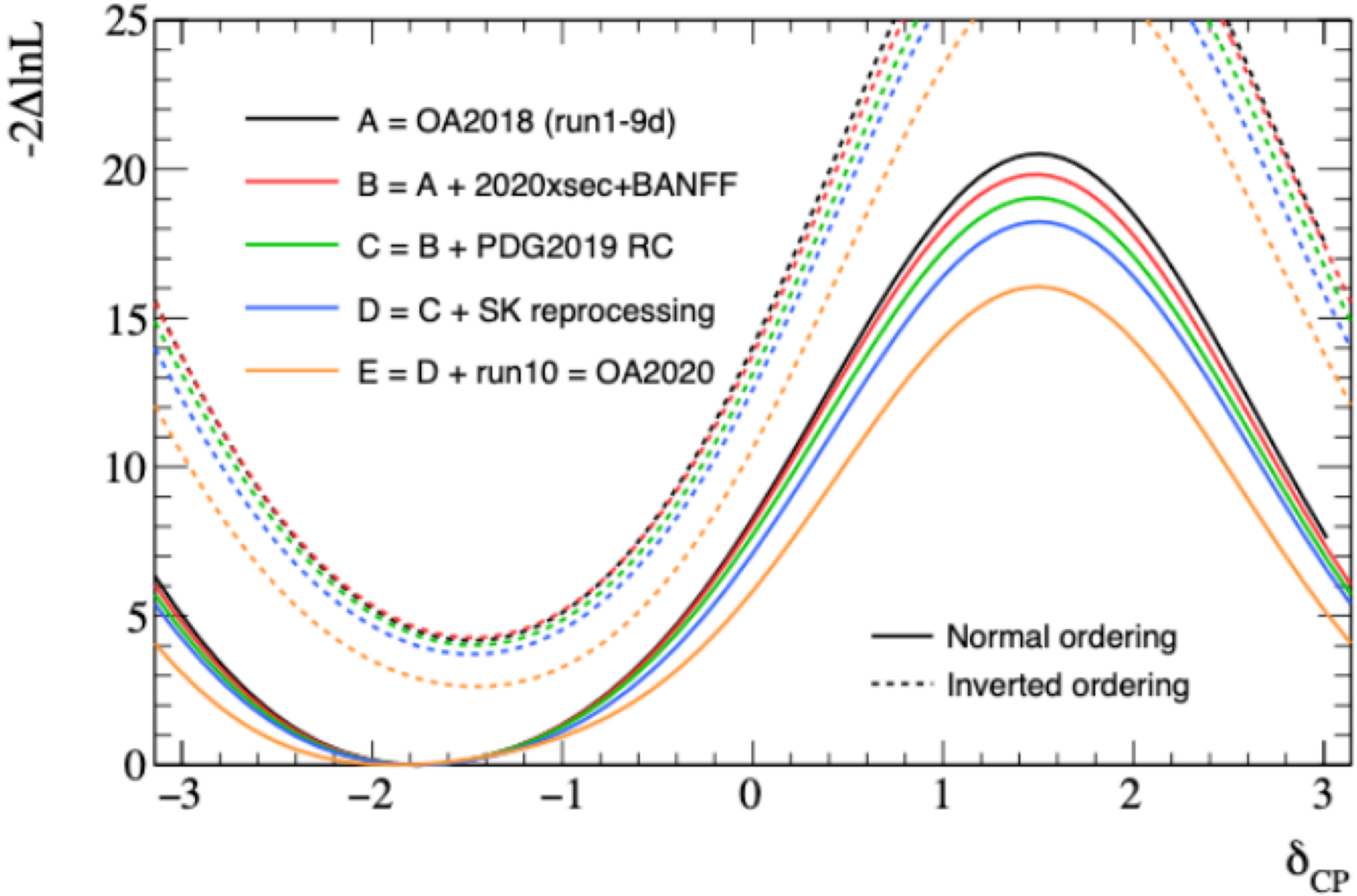


BACK-UP

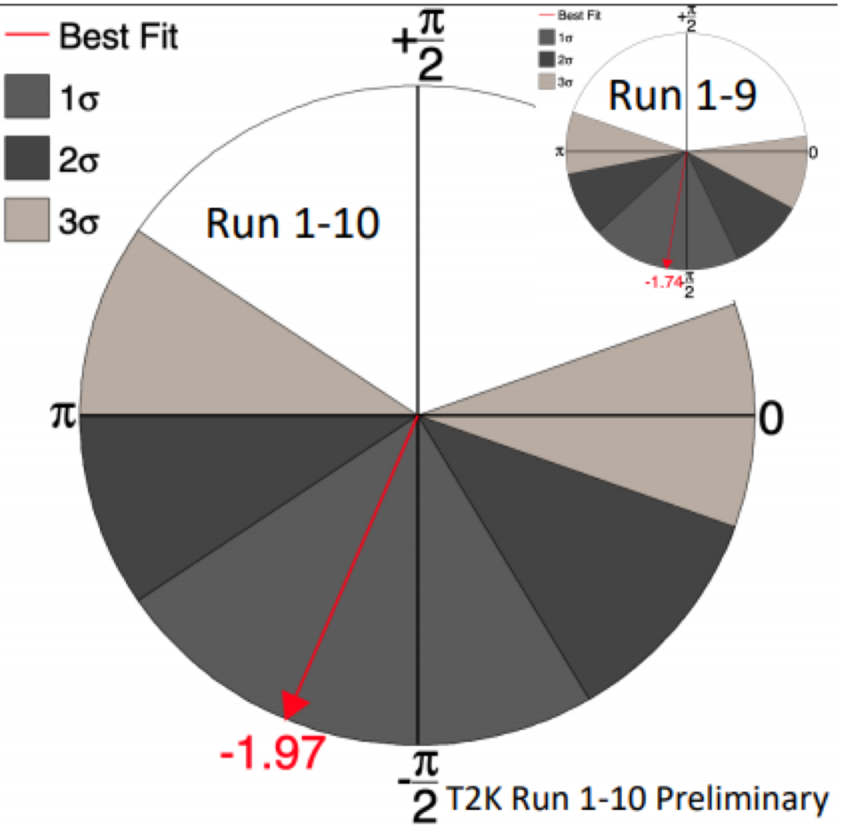
Detector uncertainties

- ND280 detector uncertainties obtained by throwing toys according to the detector systematics
- The near detector fit is performed in muon momentum and angle
- ND280 detector uncertainties are summarized in a covariance matrix indexed by the near detector binning in momentum and angle
- Previously: the MC statistical errors in this procedure were taken as the Poisson error on the bin content
- This year: we use the Barlow-Beeston procedure to account for the finite size of the MC.

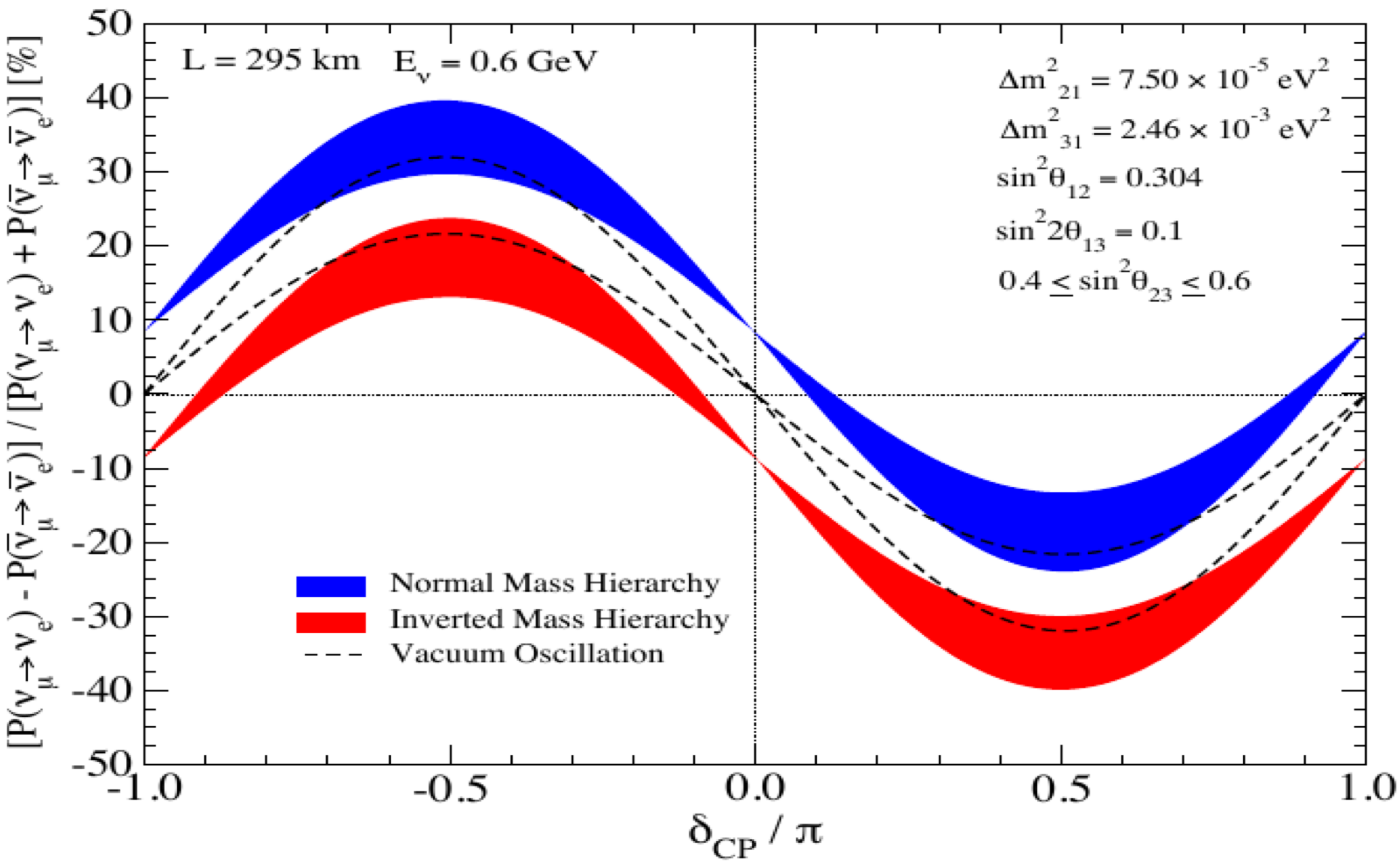
So what has changed?



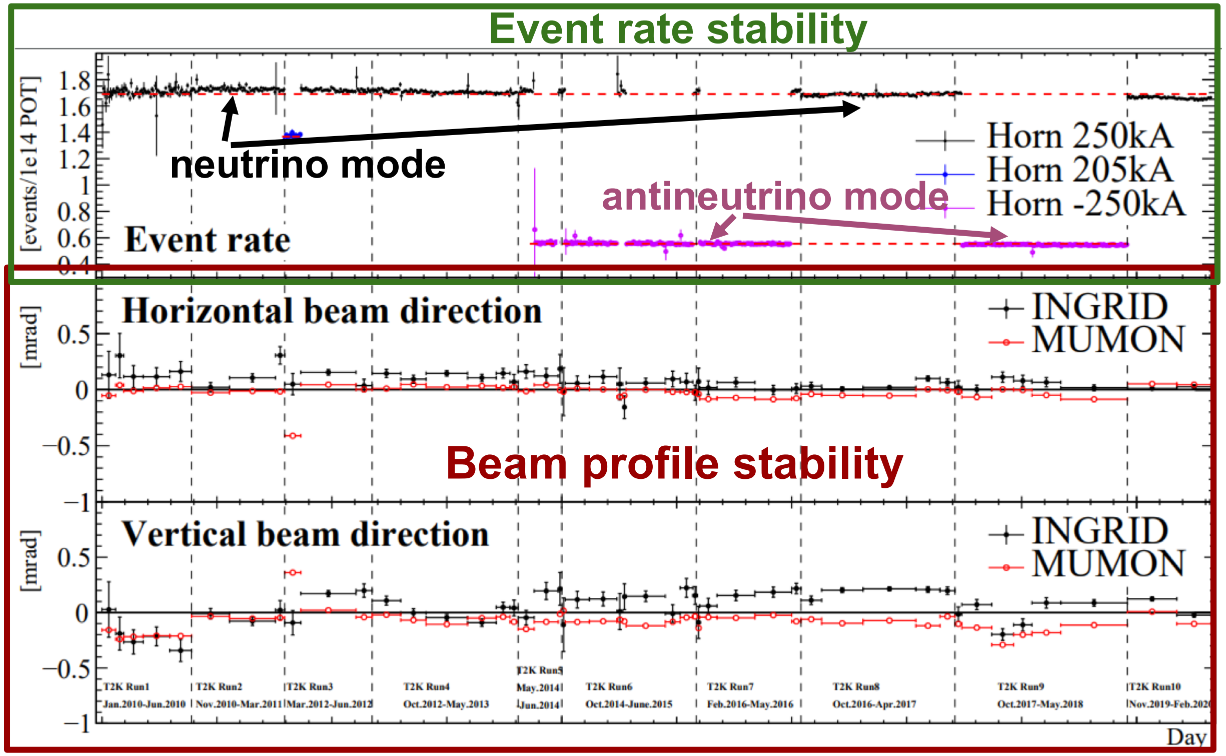
SO WHAT HAS CHANGED?

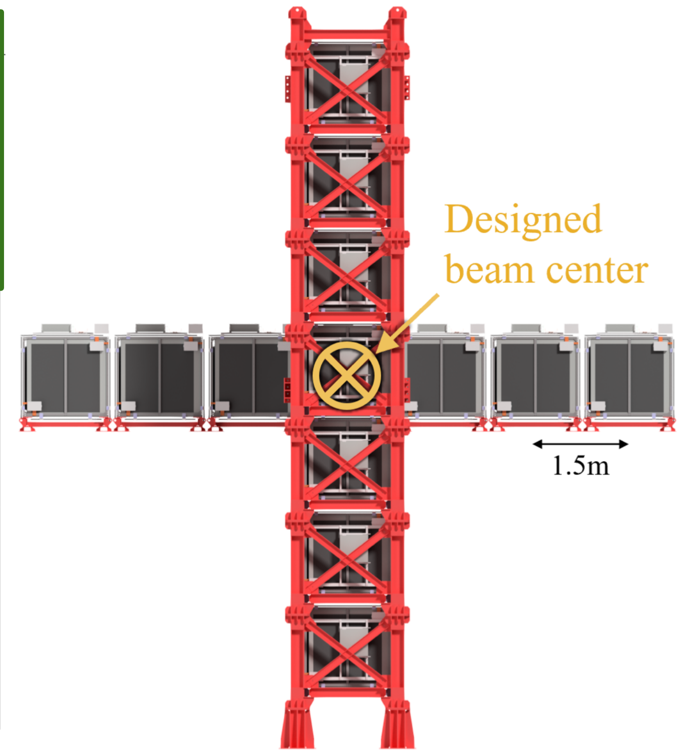


- Previous results (Nature, 580(7803), 339–344) presented a slightly tighter constraint on δ_{CP} - although the general conclusions on CP violation remain the same
- This has multiple sources:
  - the cross-section model
  - the reactor angle PDG2019 constraint
  - improved SK calibration and event reprocessing
  - adding SK run 10 (previously only runs 1-9)


L = 295 km E_ν = 0.6 GeV
$\Delta m^2_{21} = 7.50 \times 10^{-5}$ eV^2
$\Delta m^2_{31} = 2.46 \times 10^{-3}$ eV^2
$\sin^2\theta_{12} = 0.304$
$\sin^2 2\theta_{13} = 0.1$
$0.4 \le \sin^2\theta_{23} \le 0.6$
Normal Mass Hierarchy
Inverted Mass Hierarchy
Vacuum Oscillation
$[P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)] / [P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)]$ [%]
δ_{CP} / π
50
40
30
20
10
0
-10
-20
-30
-40
-50
-1.0
-0.5
0.0
0.5
1.0

INGRID



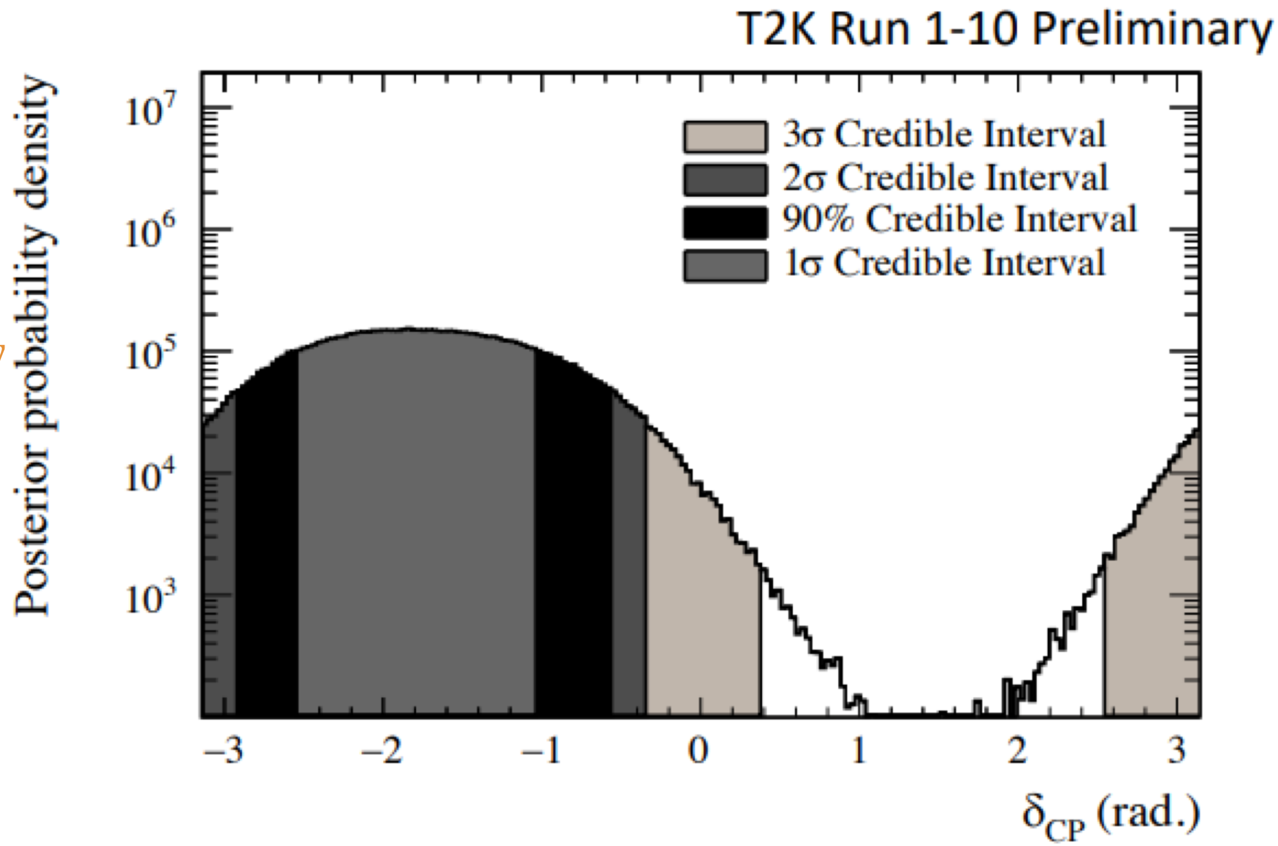


- **On-axis** detector
- Monitors beam position
- Excellent beam position and event rate stability since the beginning of T2K data taking

δ_{CP} INTERVALS (1D)

- δ_{CP} CP violating values are preferred
- Quantitatively: we exclude 35% of all δ_{CP} values at 3σ
- CP conserving values $(0,\pi)$ excluded at 90% CL
- 0 excluded at 2σ but π not quite at 2σ

Bayesian Posterior Probability



- Slight preference for upper octant and normal hierarchy

Posterior probability

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IH ($\Delta m^2_{32} < 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000