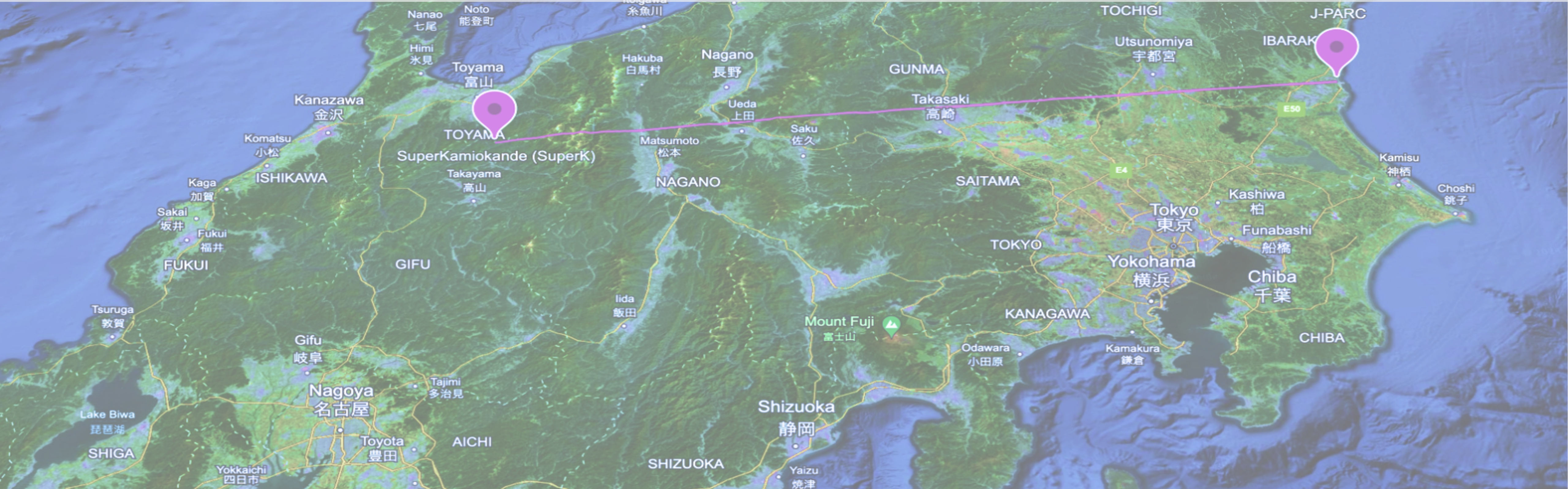
Latest Oscillation Analysis Results from T2K

Tristan Schefke
Louisiana State University



DPF-PHENO 2024

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

Neutrino Oscillations

The PMNS matrix is the simplest 3-flavor neutrino oscillation formalism capable of converting between mass and flavor bases.

This is the formalism that T2K is testing in the OA.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U_{PMNS} \cdot \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\,\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\,\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Three Mixing Angles (θ_{13}, θ_{12}, θ_{23}) → Describe relative coupling strength

CP violating phase (δ_{CP}) → Account for oscillation differences in ν and $\bar{\nu}$

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

Neutrino Oscillations

Measuring transition probabilities are our window into the PMNS matrix parameters at long baseline experiments such as T2K.

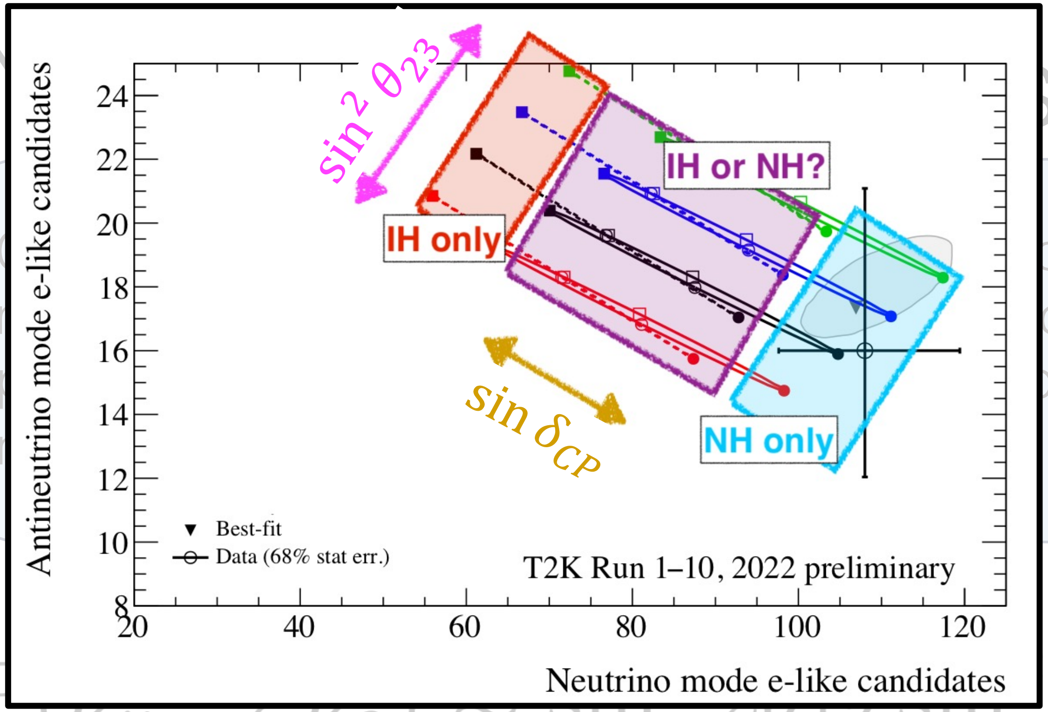
These measurements also introduce new parameters to measure such as the mass splitting for neutrinos (Δm^2_{32} and Δm^2_{21}).

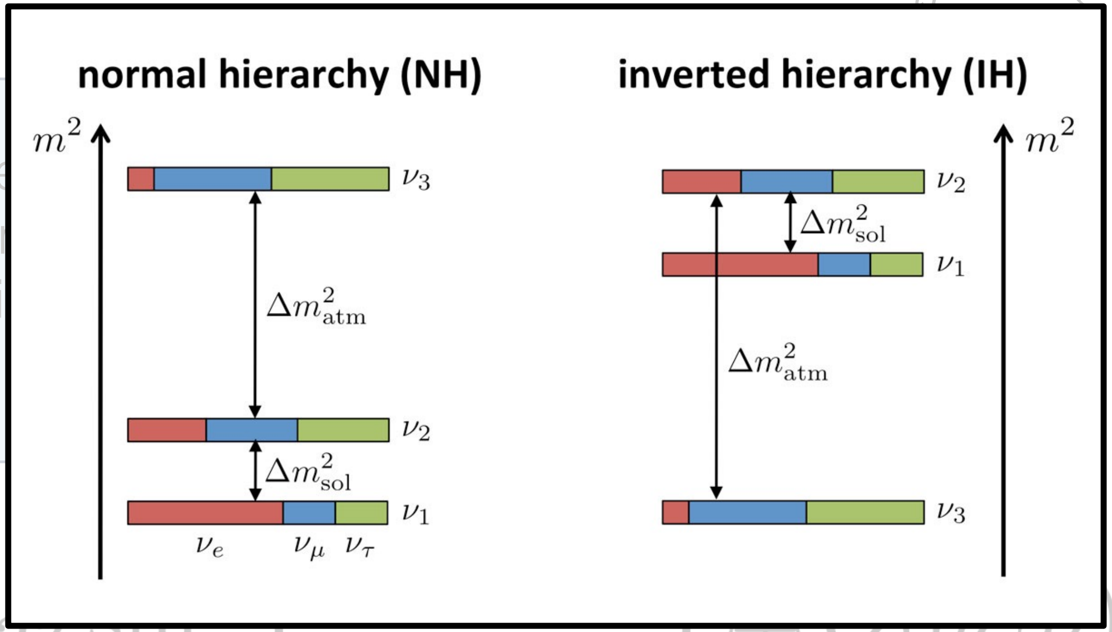
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U_{PMNS} \cdot \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right) \mp O(\delta_{CP})$$

Long baseline neutrino experiments like T2K are particularly sensitive to $\sin^2 \theta_{23}$ and Δm^2_{32} and somewhat sensitive to δ_{CP}.

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

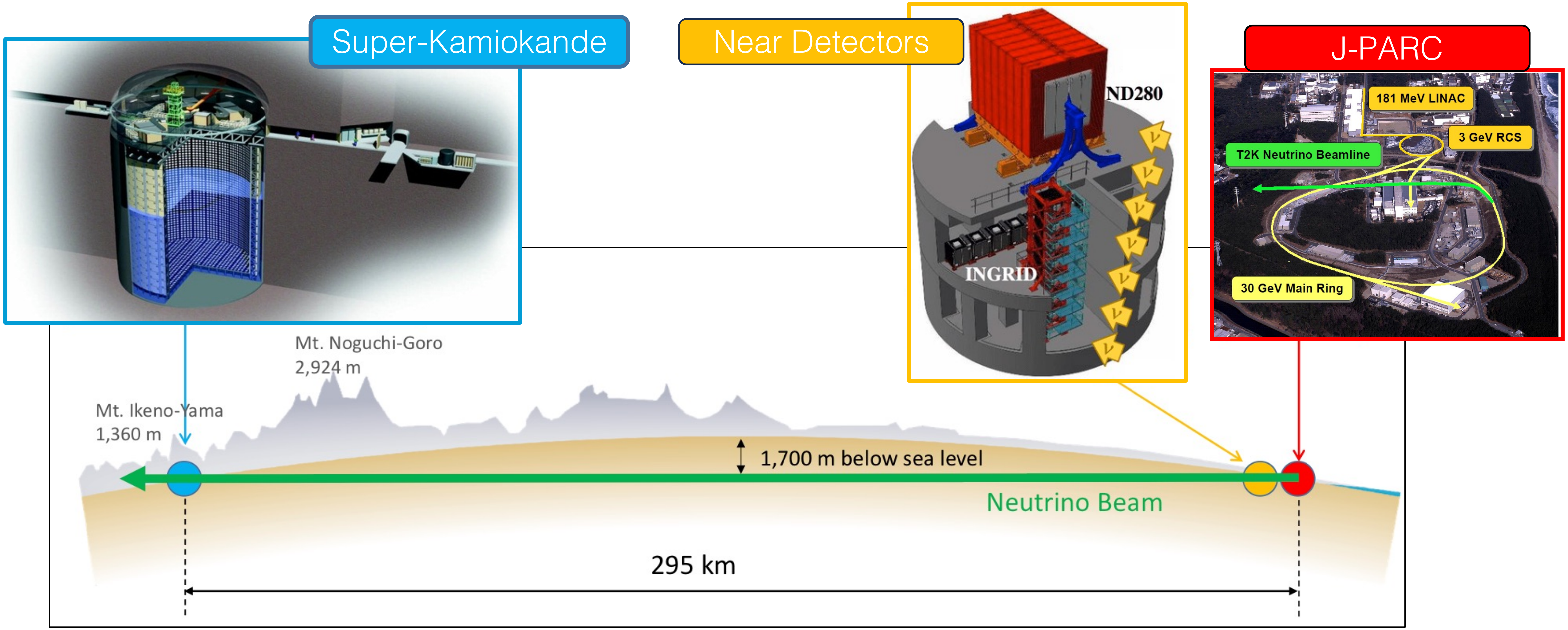




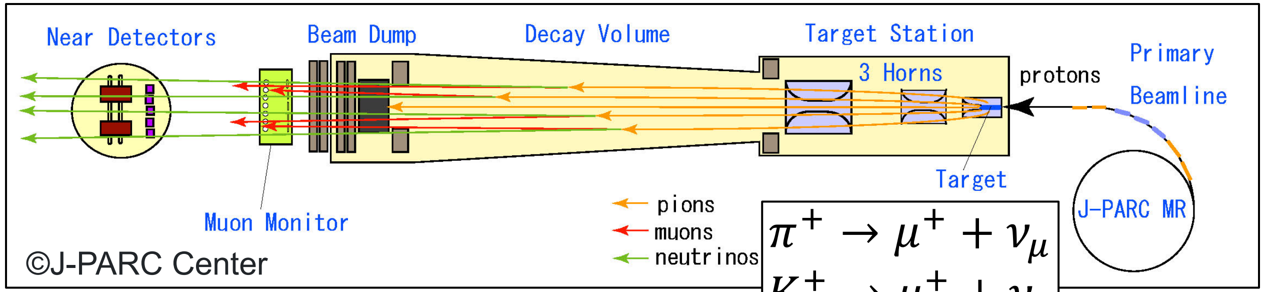
Open Questions:

- What is the value of δ_{CP}?
- What is the sign of Δm^2_{32}? (i.e. correct mass ordering)?
- Is θ_{23} maximally mixing? Which octant is the correct one?

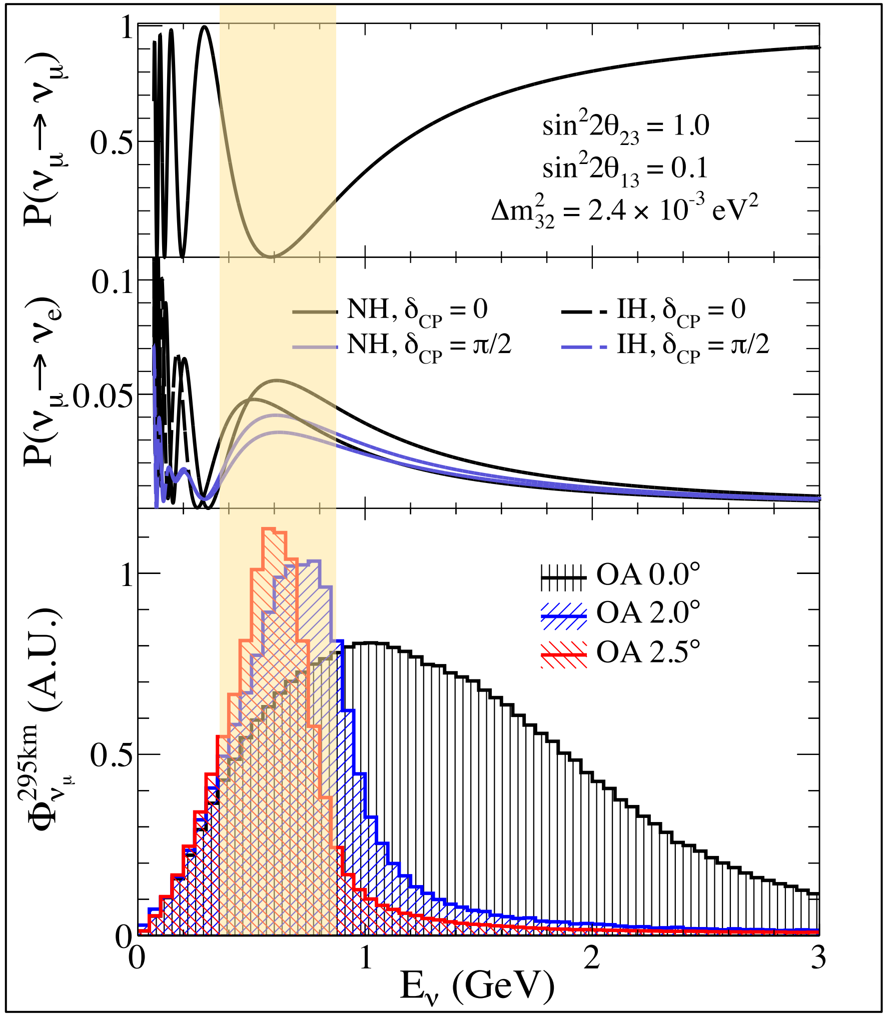
The T2K Experiment



Neutrino Beam Production



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$K^+ \rightarrow \mu^+ + \nu_\mu$$



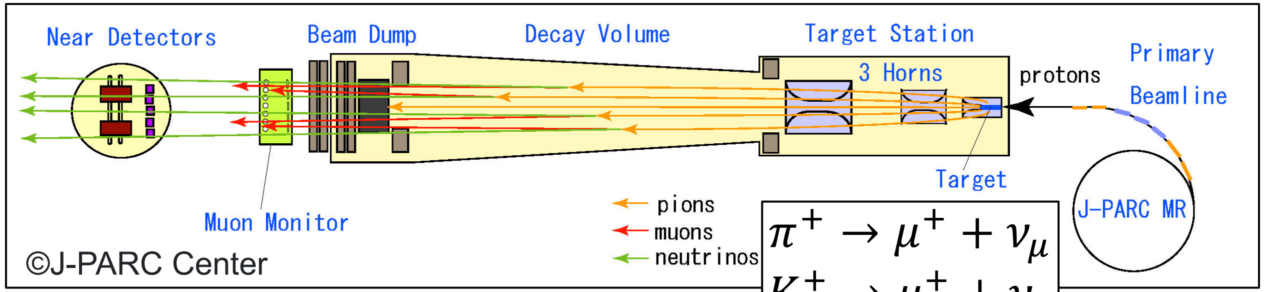
Produces anti-neutrinos and neutrinos by colliding protons on a monolithic graphite target.

T2K employs the off-axis method (2.5°) to reduce spread in the neutrino beam.

Main neutrino beam peaks at 0.6 GeV

- Primary interactions at T2K are CCQE

Neutrino Beam Production



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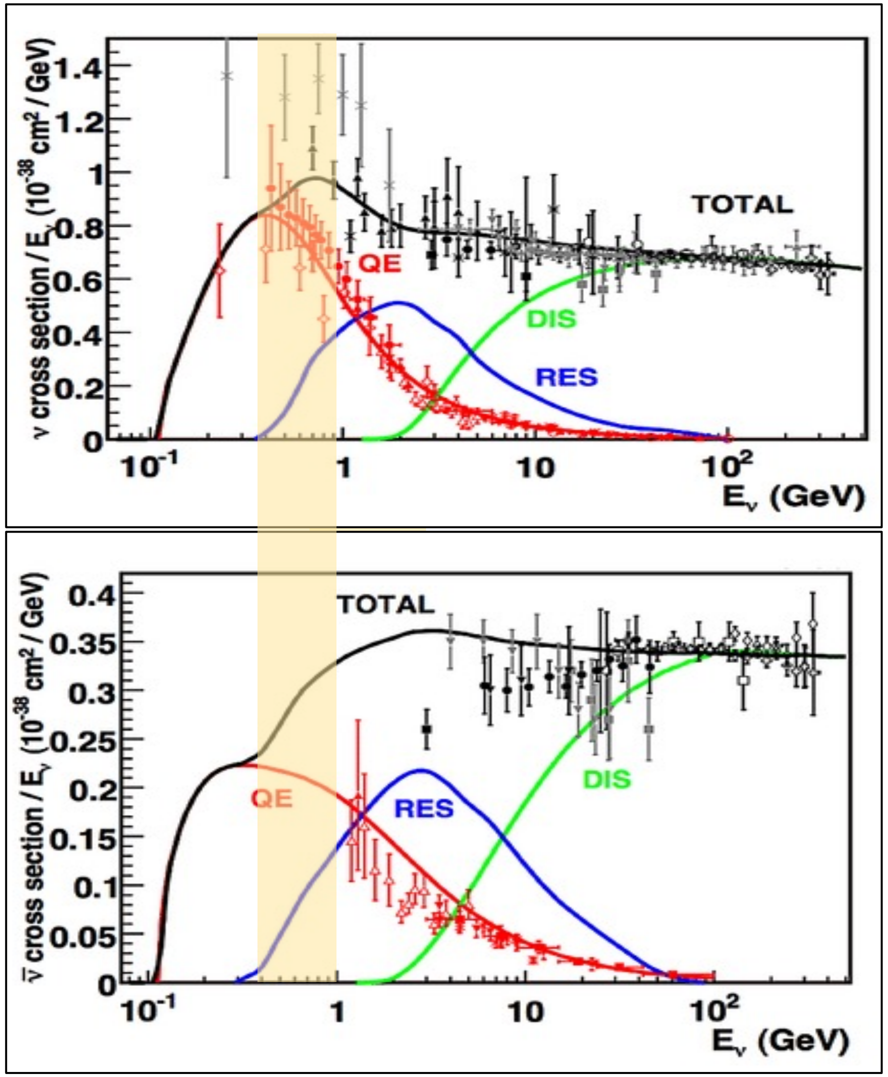
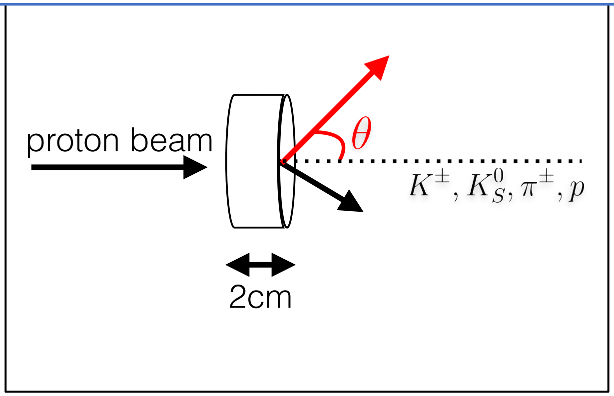
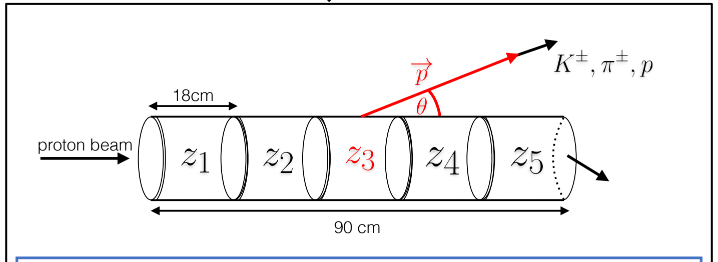


https://doi.org/10.1103/RevModPhys.84.1307

Updated Flux Modelling

Thin Target Hadron Production Data



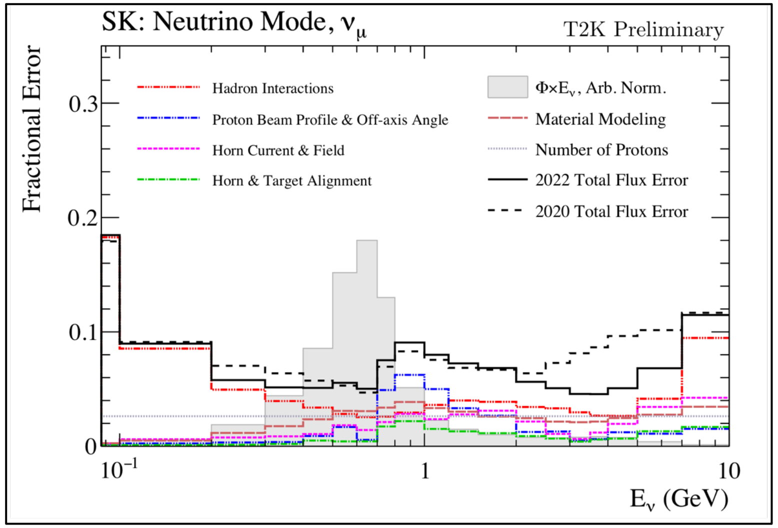


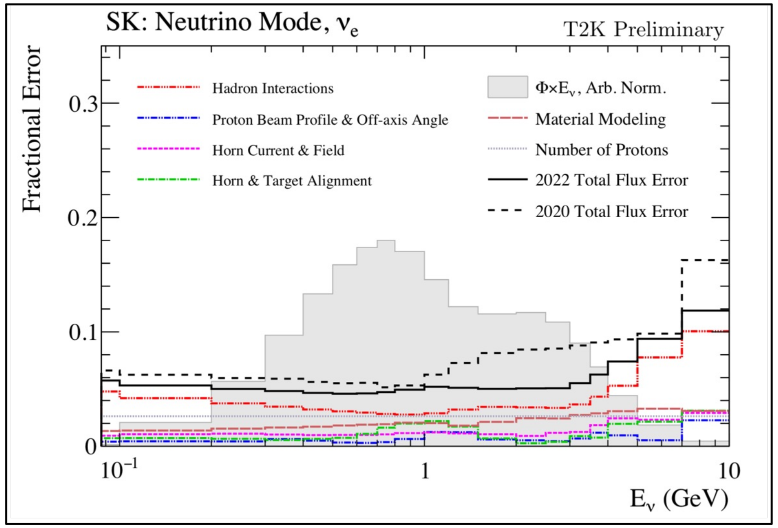
Realistic Hadron Production Data

This analysis is the first to use additional hadron production data from a replica T2K target collected by NA61/SHINE

Also uses a new GEANT4-based simulation (from FLUKA/GEANT3) with updated cooling water modelling in magnetic horns.

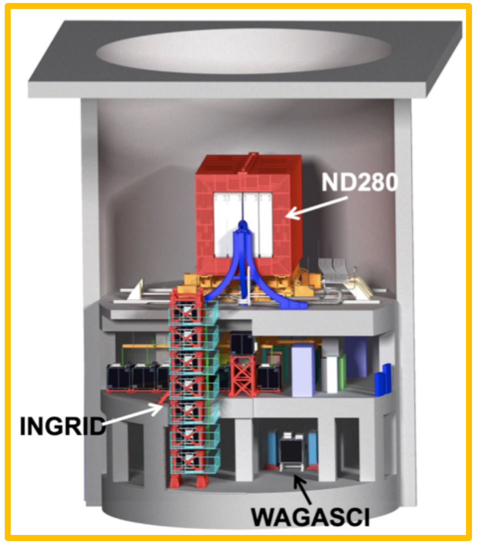
Neutrino flux prediction uncertainties reduced to sub 5% in peak neutrino flux region.

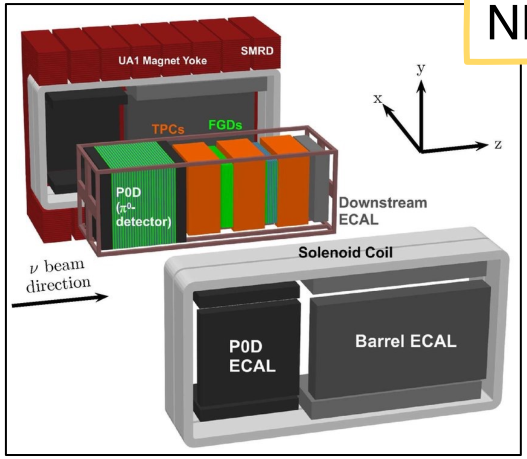




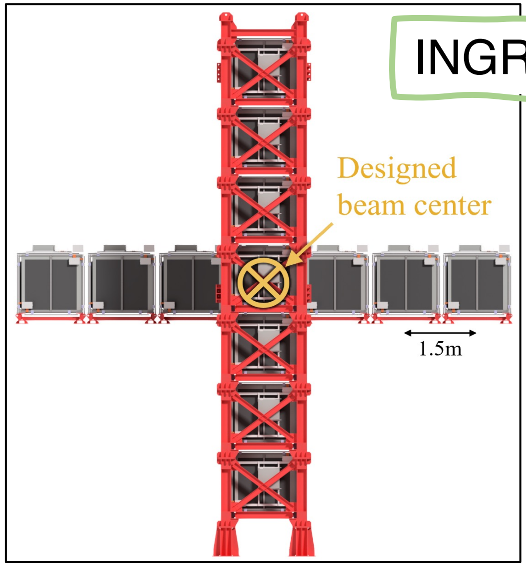
See Lu Ren's talk on NA61/SHINE

The Near Detectors

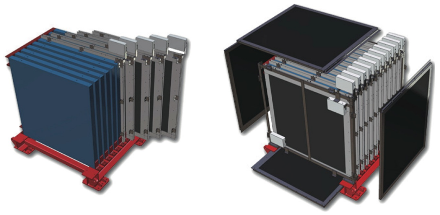




ND280



INGRID



ND280

- Off-axis detector (2.5º)
- 0.2T Magnet
- 3 **TPCs**: gAr Time Projection Chambers
- 2 **FGDs**: C and C+H_2O Fine Grained Detectors.
- **P0D**: π^0 detector
- **SMRD**: Side Muon Range Detectors
- **ECAL**: Electromagnetic Calorimeters

INGRID

- On-axis Detector
  - Monitors beam profile and stability from ν_μ CC interactions.
  - 14 Fe/Scintillator modules

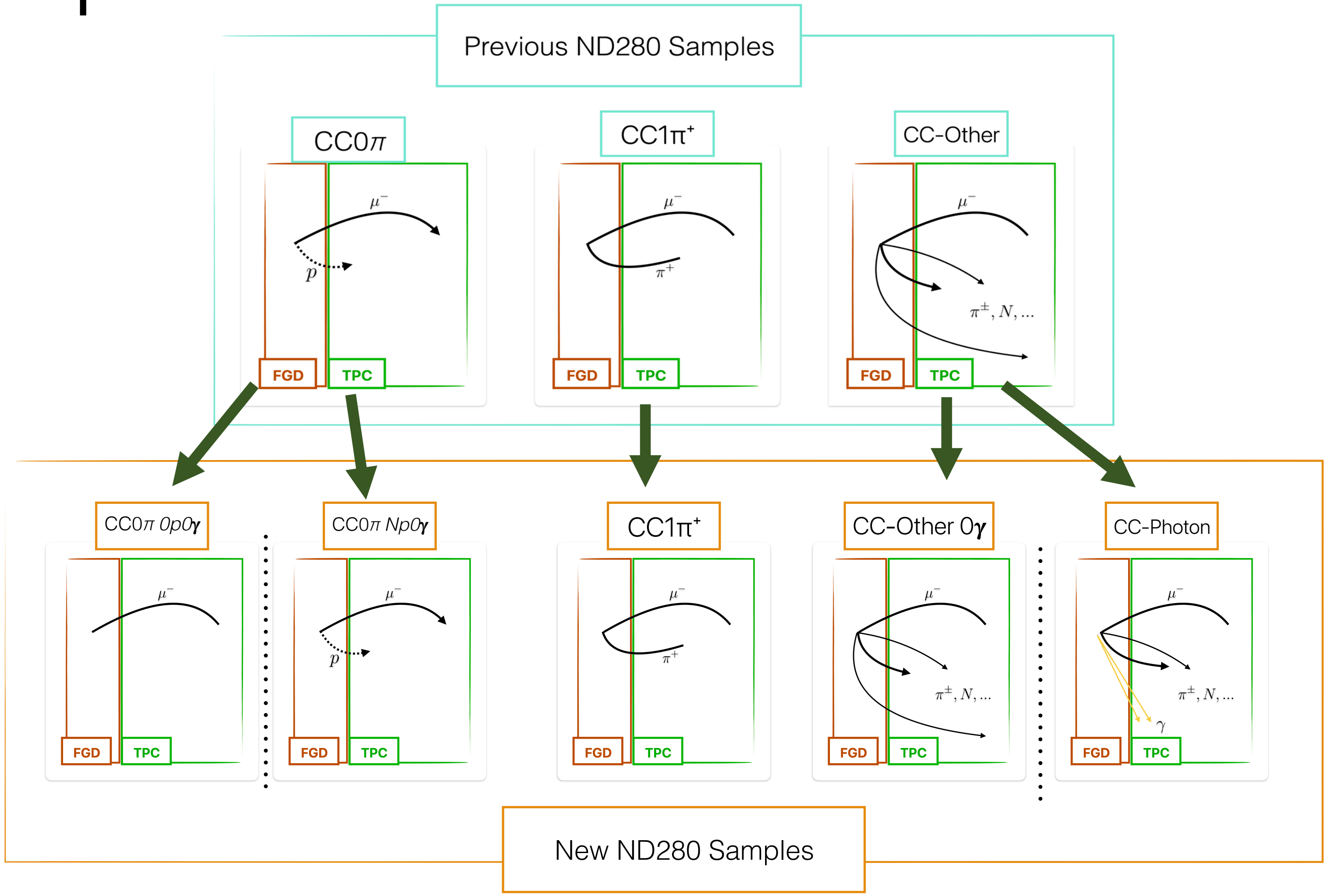
New ND280 Samples

ν_μ samples from previous OA updated to improve constraints on flux and cross-section parameters.

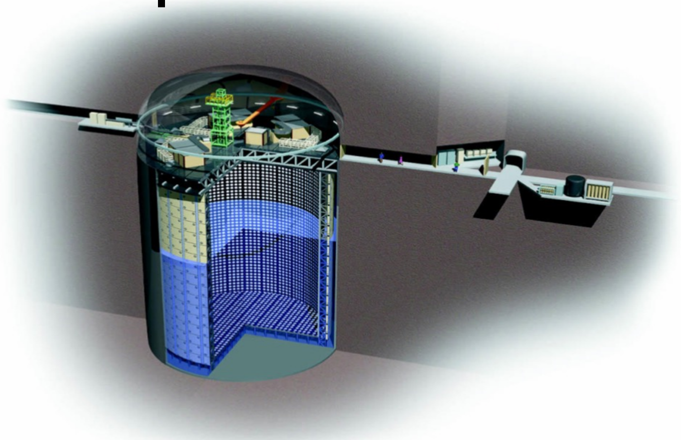
Similar event selection performed for $\bar{\nu}_\mu$ **except**:

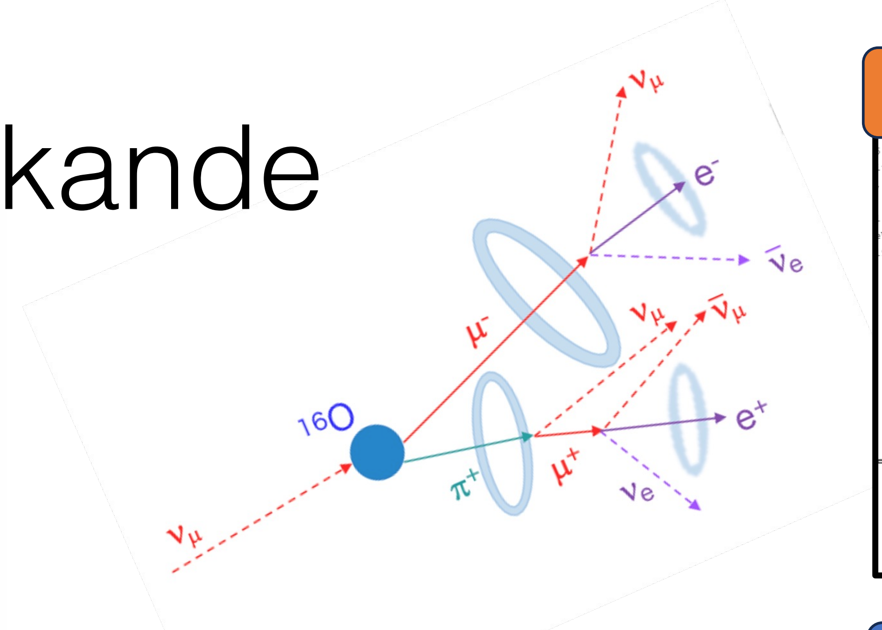
- ➢ Without tagged proton and photons
- ➢ ν_μ selections performed to reduce background contamination.

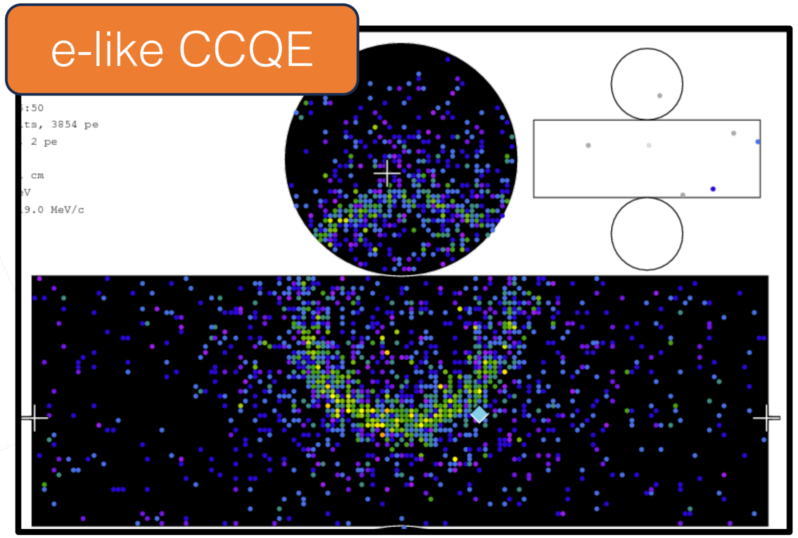
In total, 22 samples reconstructed at the near detector.



Super-Kamiokande



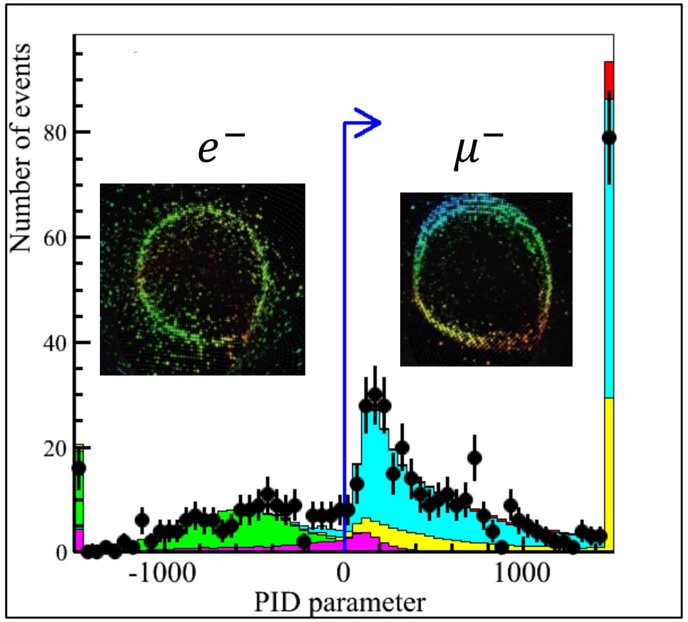


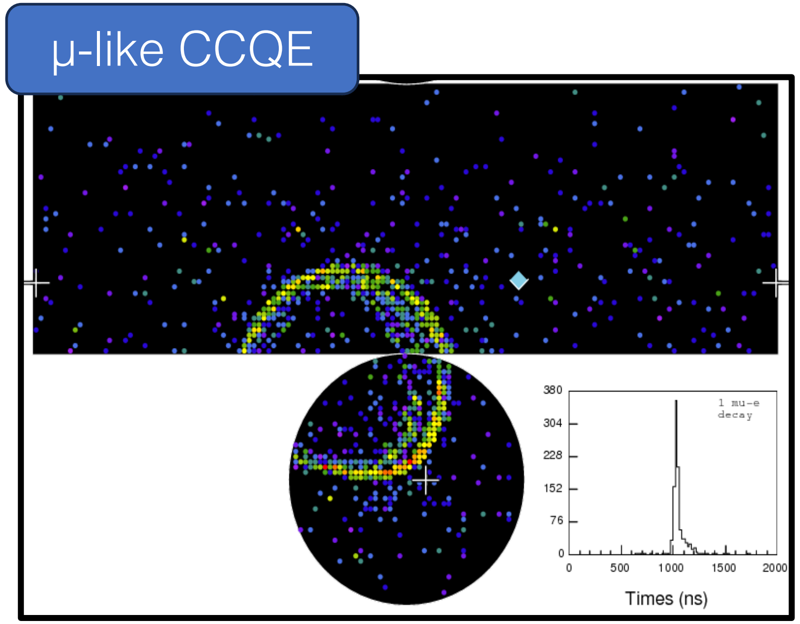


50 kTon water Cherenkov detector

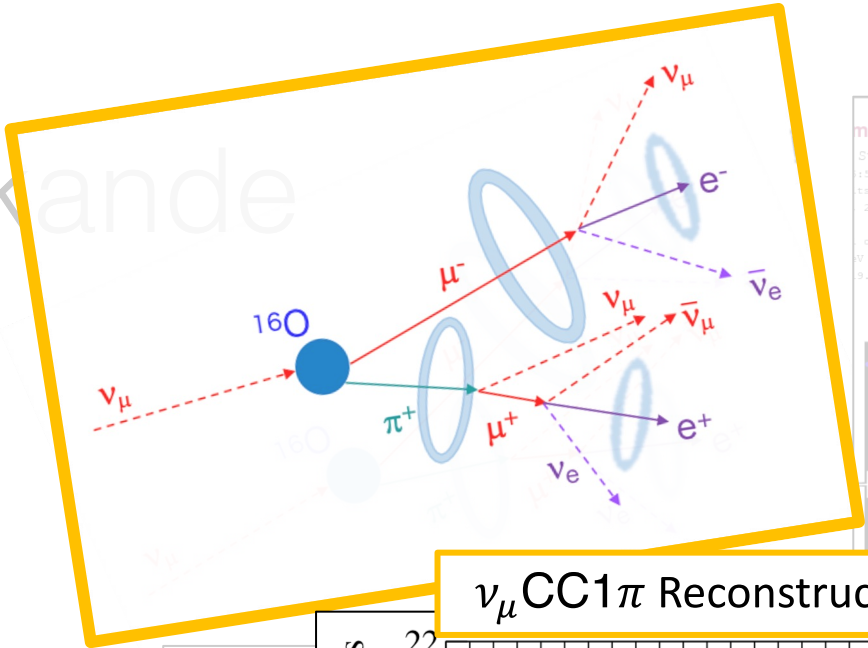
➢ ~11,000 PMTs in Inner Volume

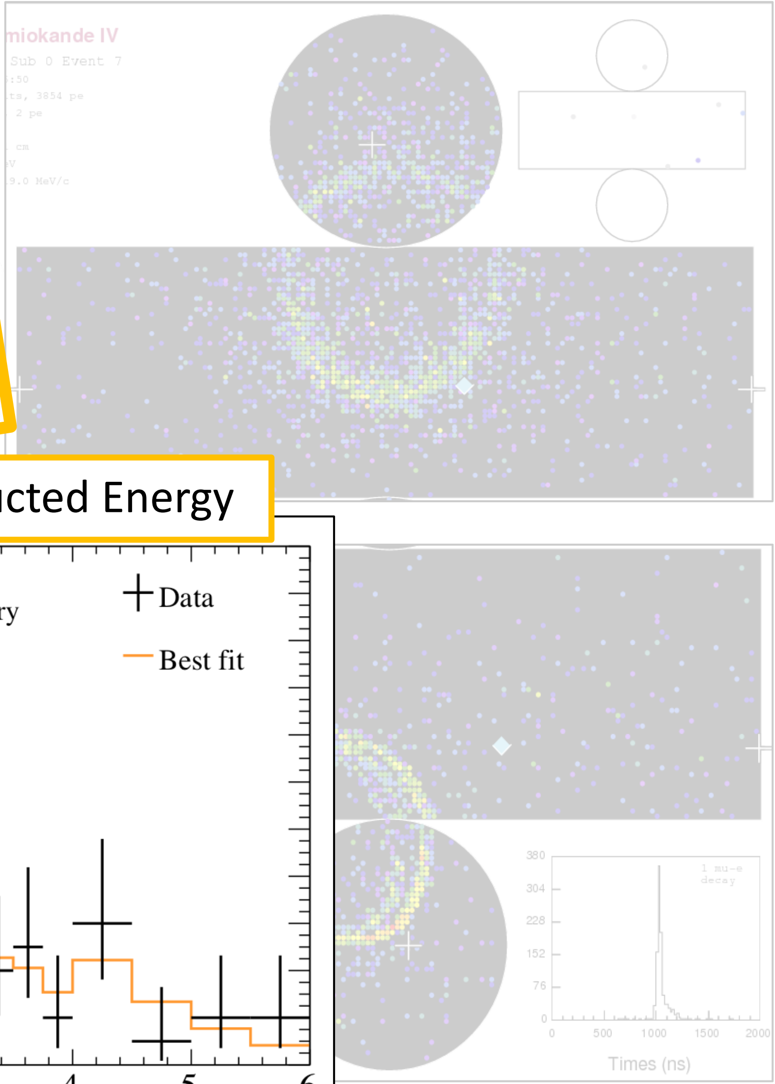
Differentiates Cherenkov rings between μ/e with 1% mis-tagged around peak neutrino energies (0.6 GeV).



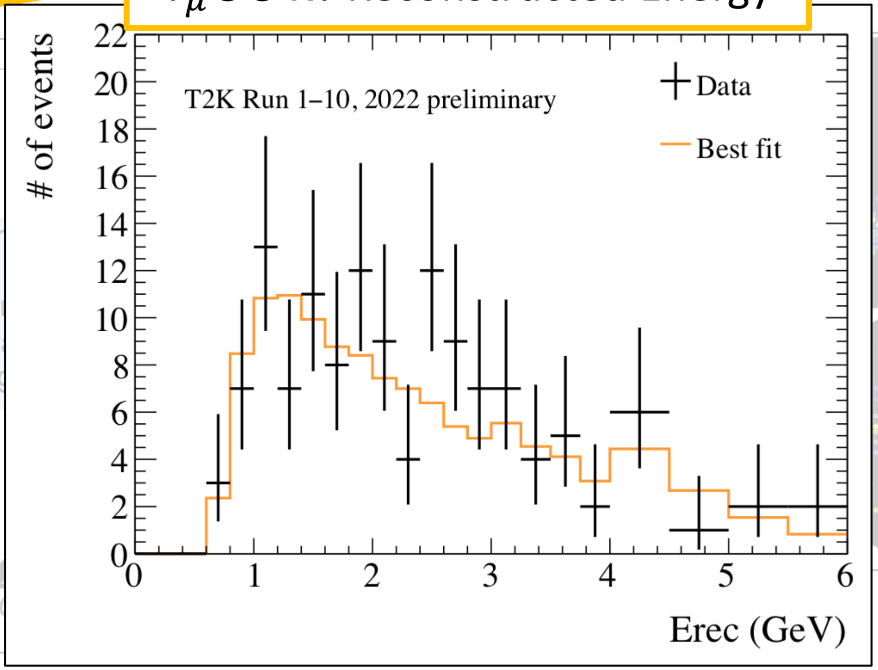


Super-Kamiokande





ν_μCC1π Reconstructed Energy



This analysis uses the first multi-ring sample from ν_μCC1π interactions at the far detector.

Statistics in ν_μ configuration also increased by ~30% from previous analysis.

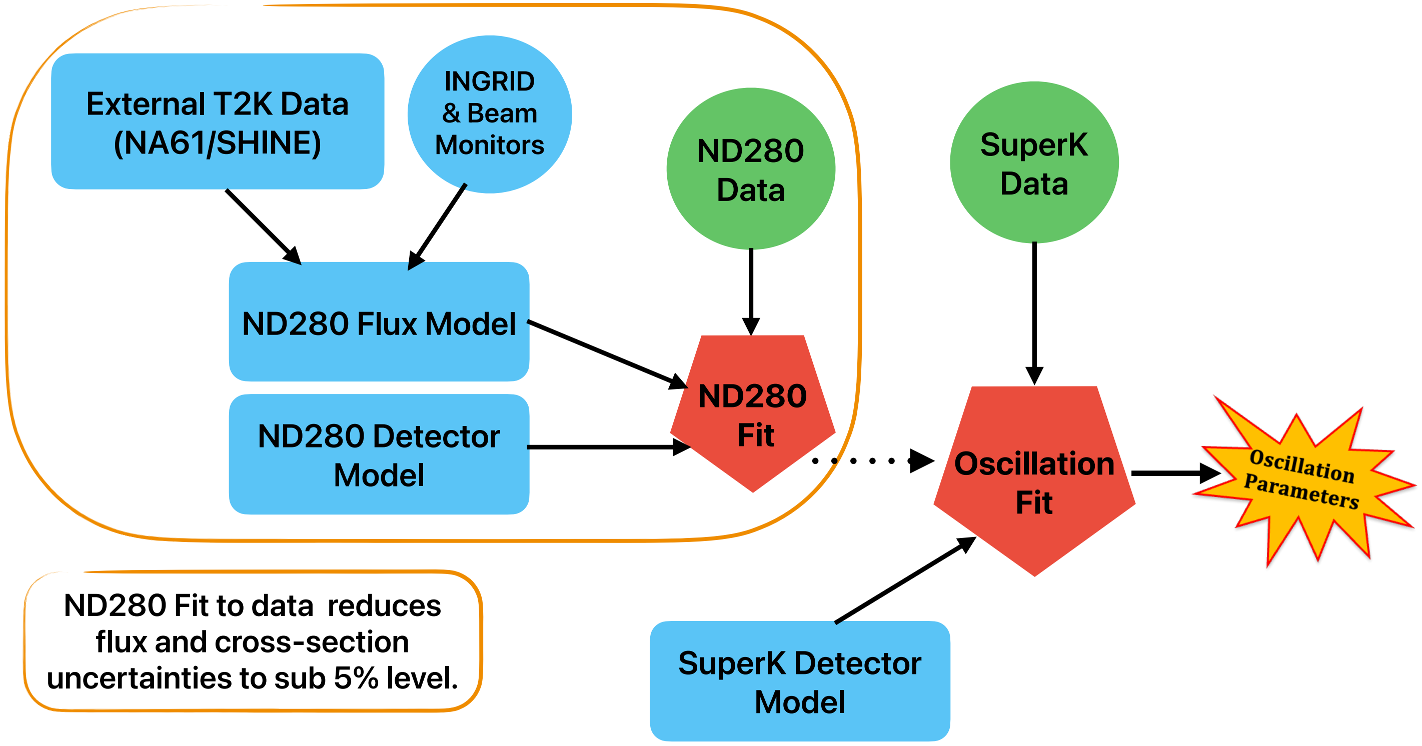
Hybrid-Frequentist Analysis Strategy

Utilizes constraints from a near detector fit for the far detector data fit.

Systematic uncertainties in this fit are modelled with a Gaussian penalty term.

Effect of finite MC covered by statistical methods proposed by Barlow and Beeston.

Confidence Levels estimated by Feldman-Cousins.

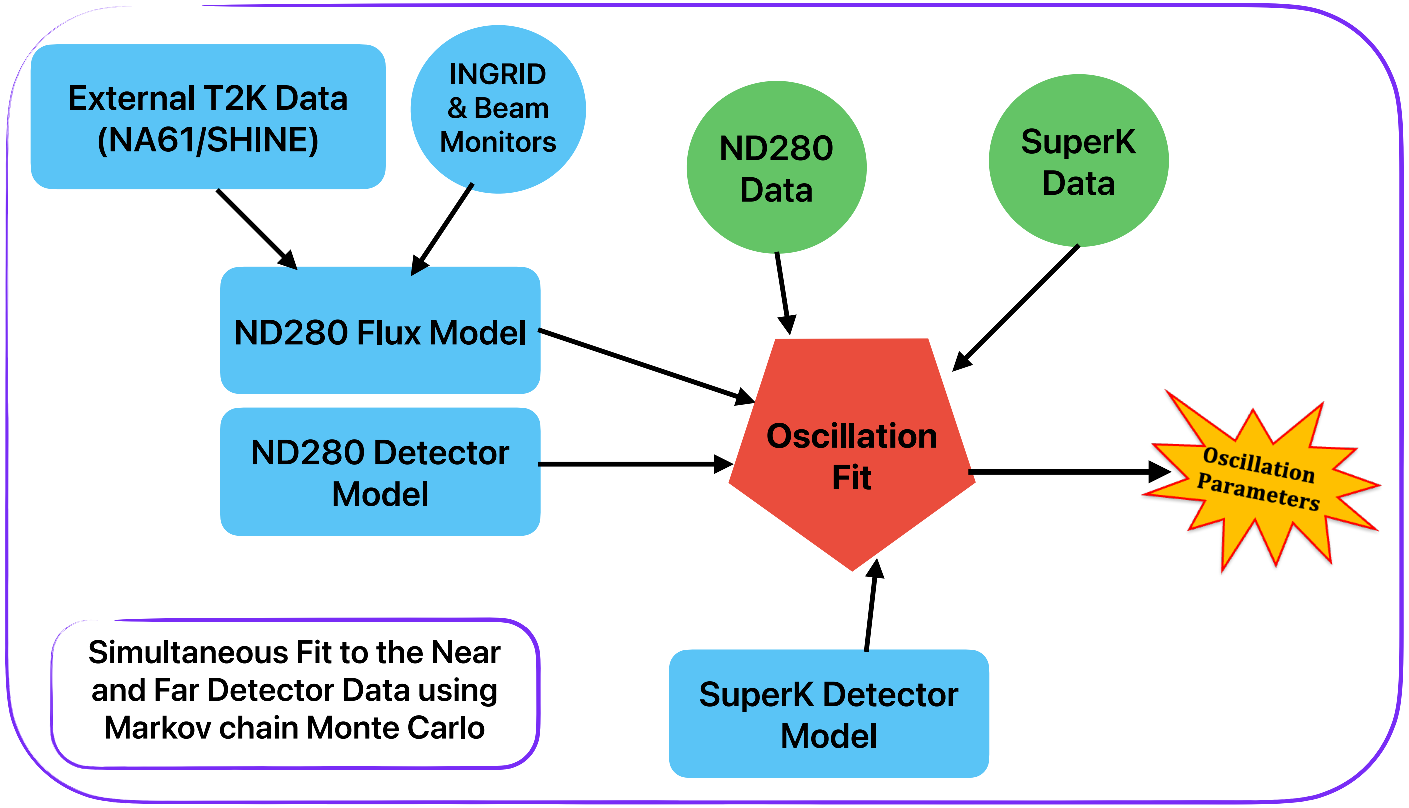


Bayesian Analysis Strategy

Uses Markov-Chain Monte Carlo to sample posterior distributions constructed from MC.

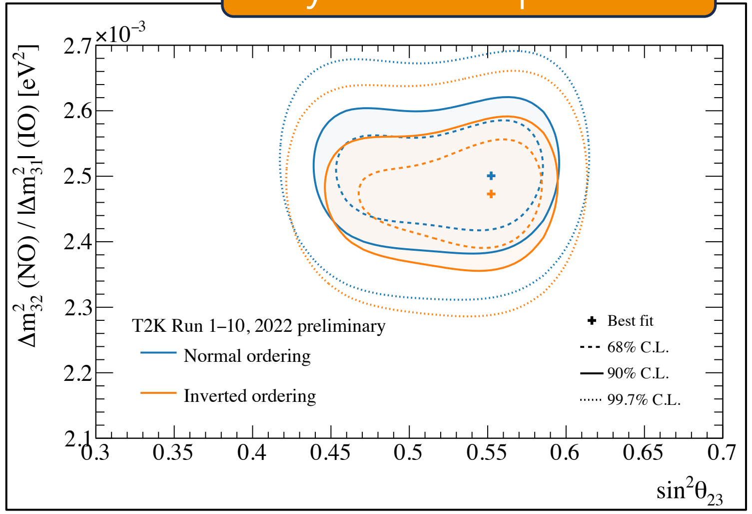
Systematic uncertainties treated the same as Hybrid-Frequentist approach.

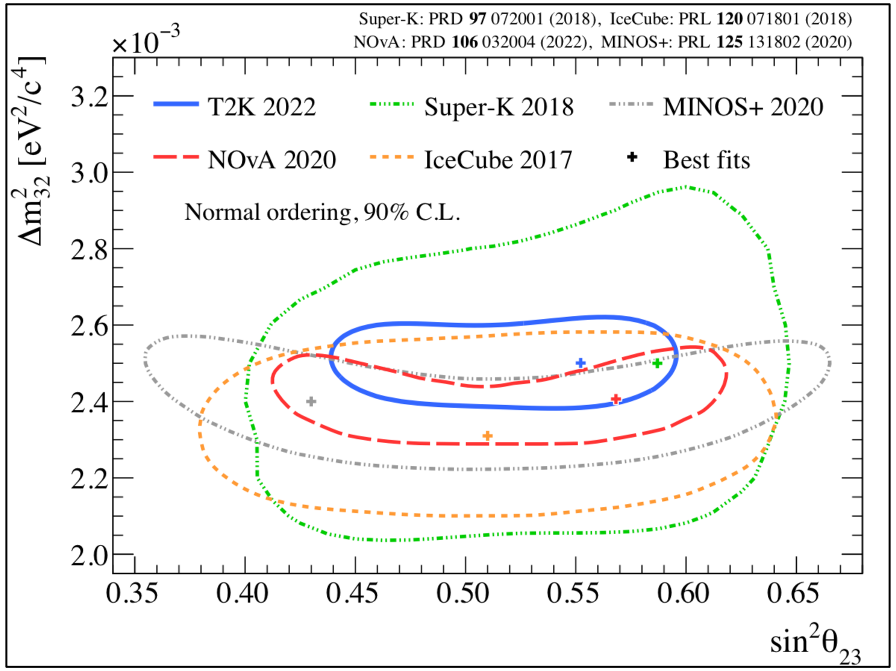
Credible intervals estimated from marginalized posterior distributions.



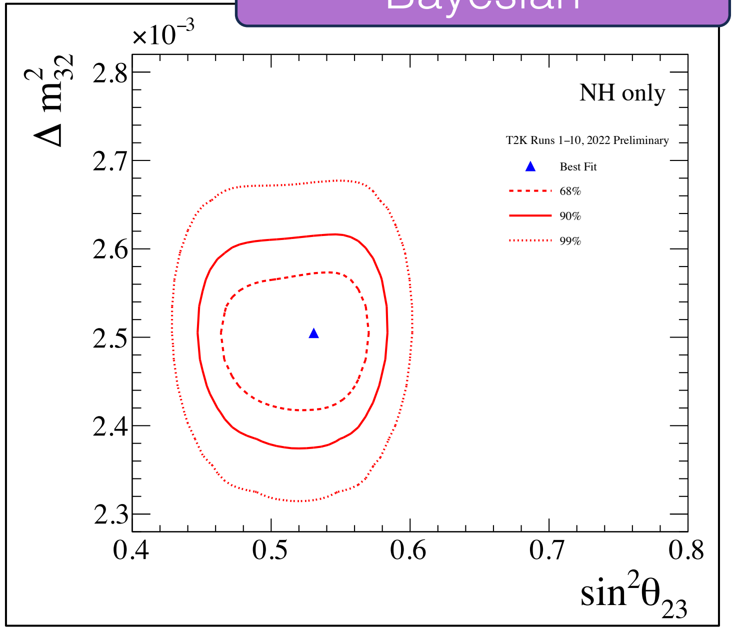
Results: 2D Contours θ_{23} vs. Δm^2_{23}

Hybrid-Frequentist





Bayesian

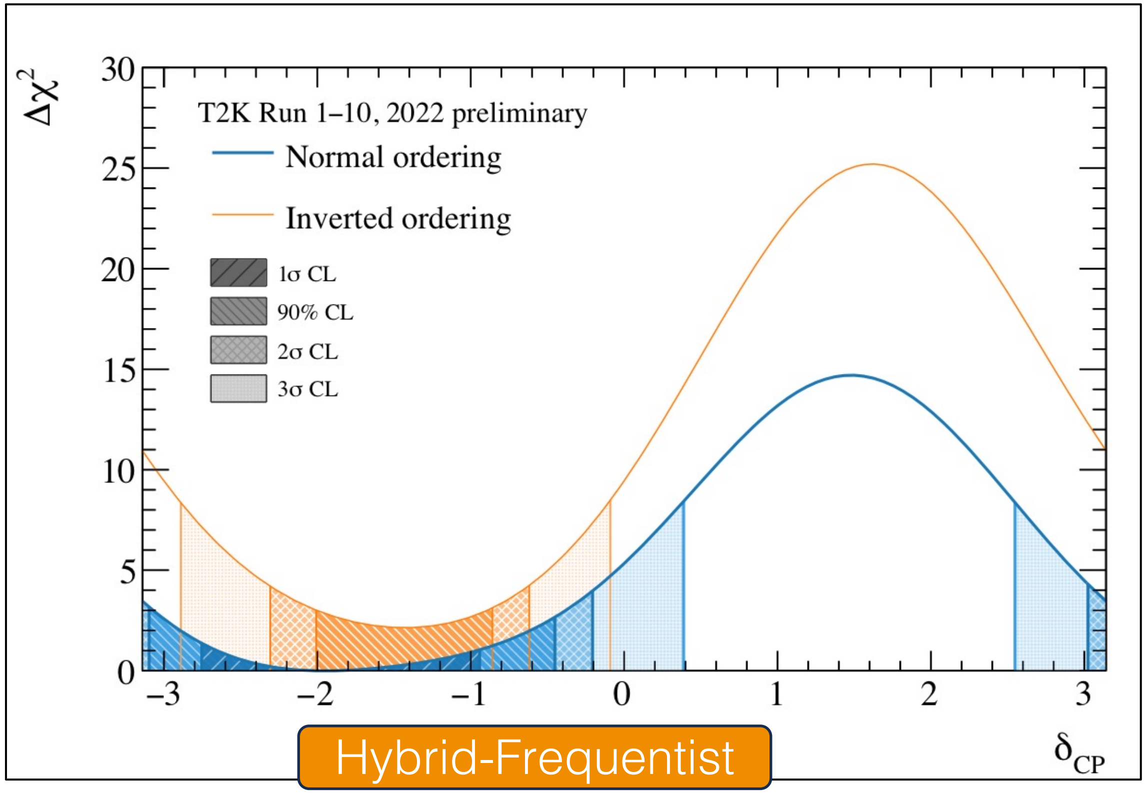


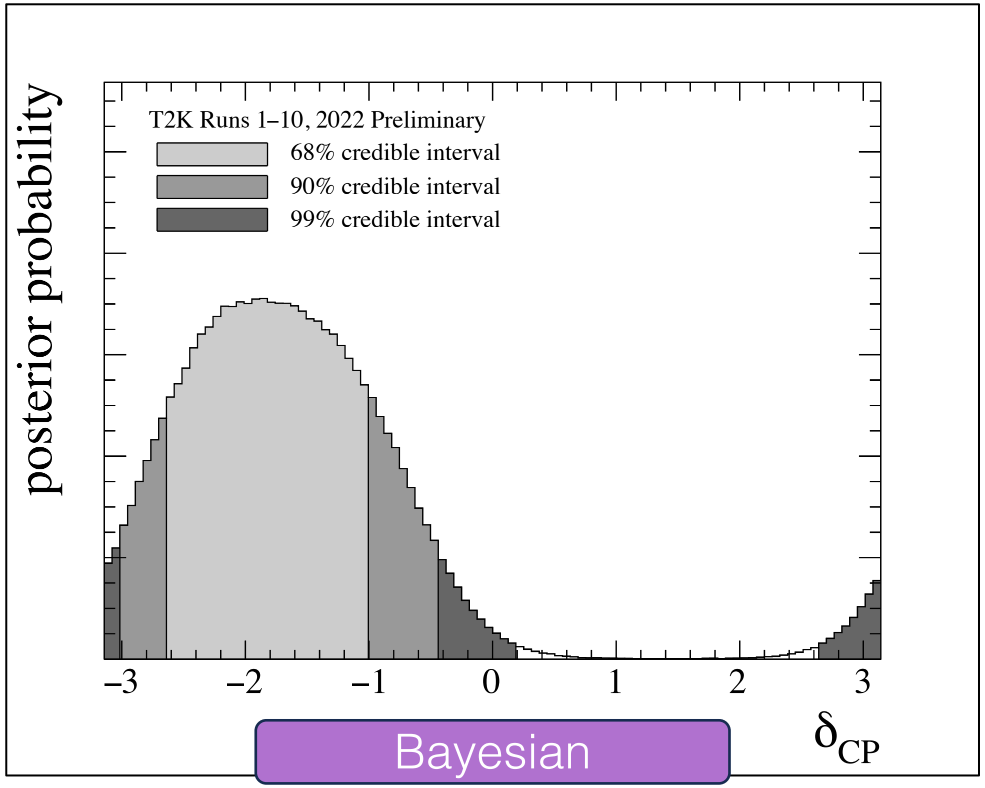
T2K currently has the world-leading measurement on Δm^2_{32} and $\sin^2\theta_{23}$

- $\Delta m^2_{32}/10^{-3}$ (Hybrid-Frequentist): $2.494^{+0.041}_{-0.058}$
- $\sin^2\theta_{23}$ (Hybrid-Frequentist): $0.561^{+0.017}_{-0.056}$

Results shown here apply reactor constraint ($\sin^2 2\theta_{13} = 0.0861 \pm 0.002$)

Results: CP Violation in Neutrino Oscillations, δ_{CP}





Hybrid-Frequentist and Bayesian results rule out some CP-conserving values at the 2σ CL and 90% CI respectively. Both approaches favor values near maximal CP violation ($-\pi/2$).

- $\delta_{CP} = -1.97^{+0.97}_{-0.62}$

Results shown here apply reactor constraint ($\sin^2 2\theta_{13} = 0.0861 \pm 0.002$)

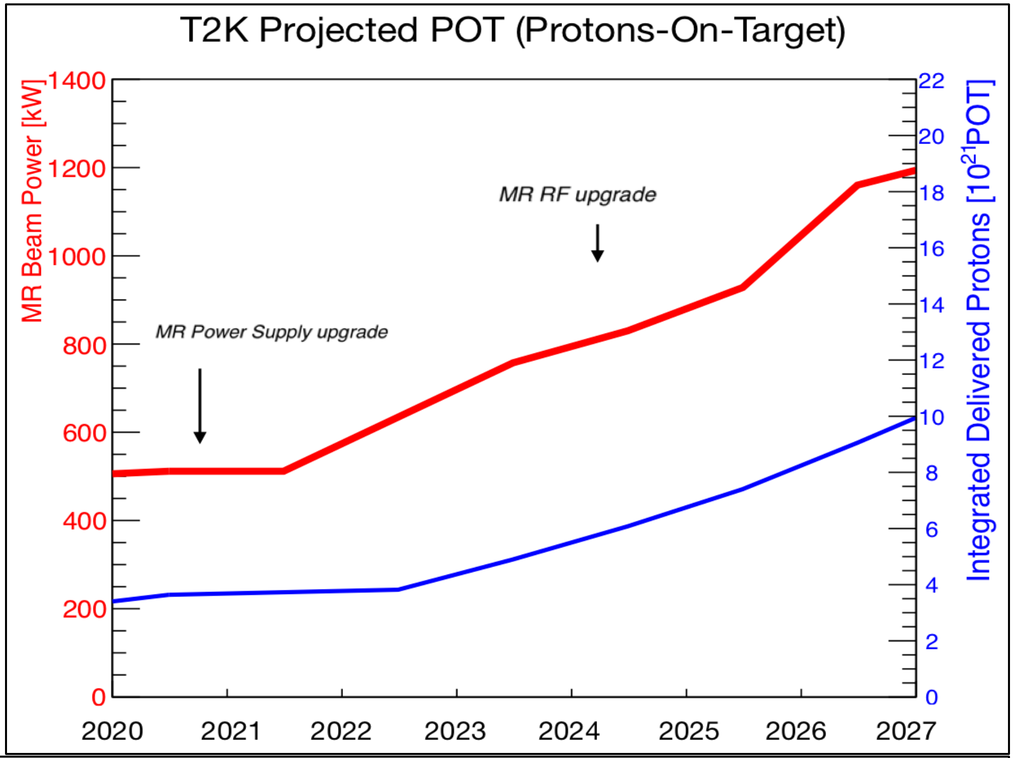
Future Outlook

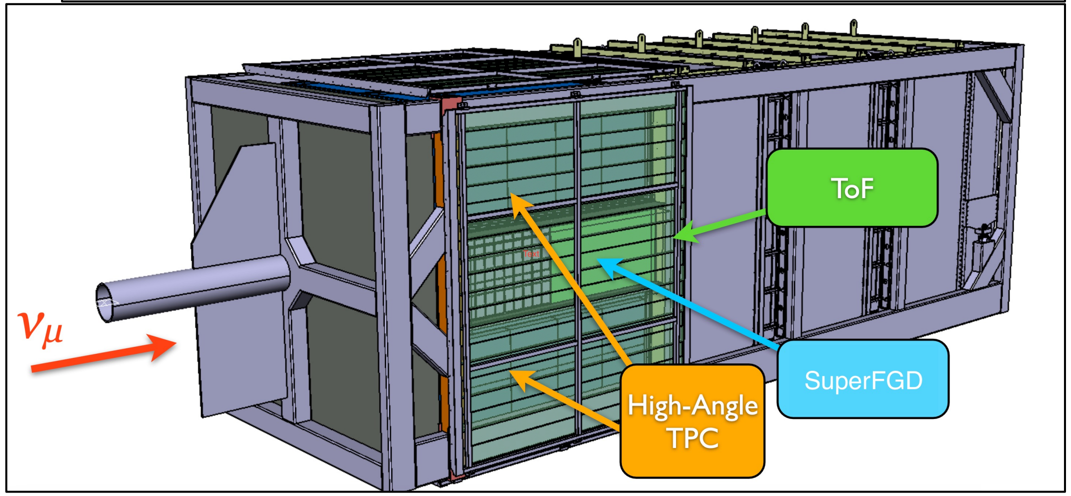
T2K data taking will continue until 2027 when Hyper-Kamiokande will begin data-taking.

- ➢ Increased beam power → more POT!
- ➢ Increased horn current → more separation power between $\nu_\mu/\bar{\nu}_\mu$

T2K data collected later this year will include our recent near detector upgrade.

See Eric Chong's talk on Thursday afternoon!





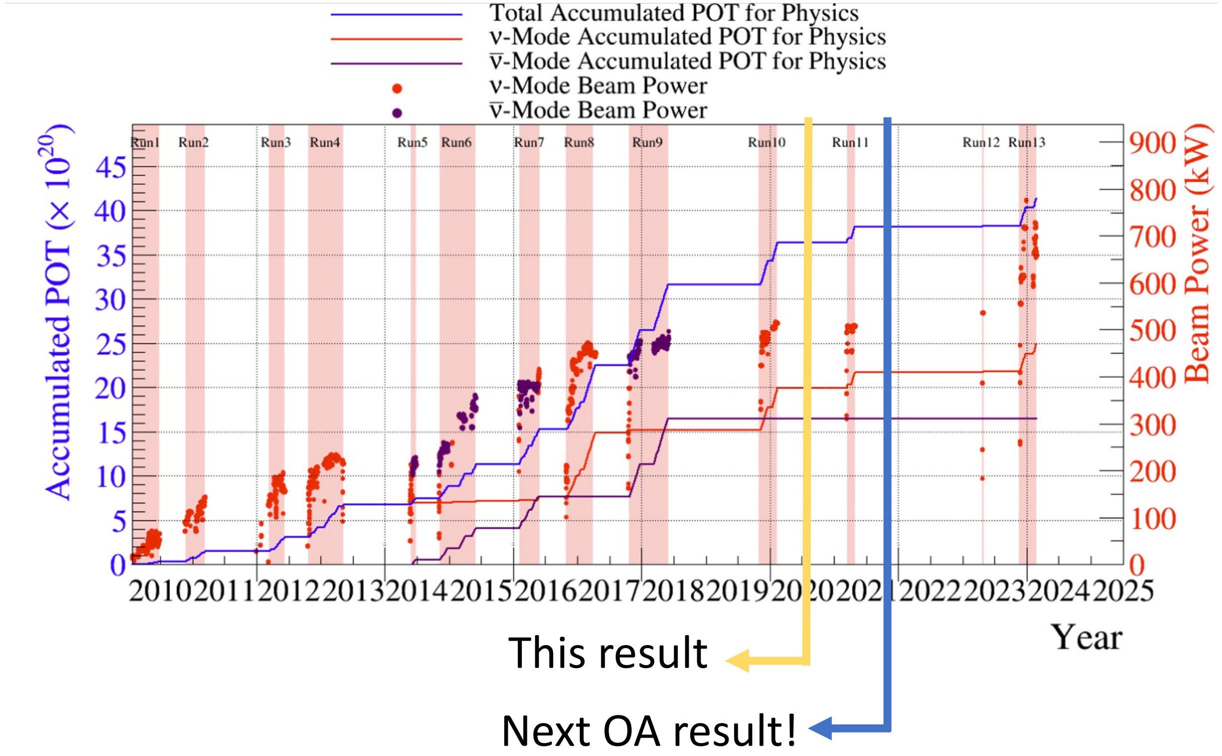
Upcoming Results

Next oscillation analysis is under internal review but includes many new changes including

- ≃ 9% increase in FHC data
- First data set with Gd-loading at Super-Kamiokande.
- Improved treatment of detector error matrix at the far detector.

Next to next oscillation analysis is currently underway! Changes include:

- Further improvements to cross-section model at the near detector
- New ND samples with 4pi solid angle acceptance.
- New multi-ring event selections at FD!



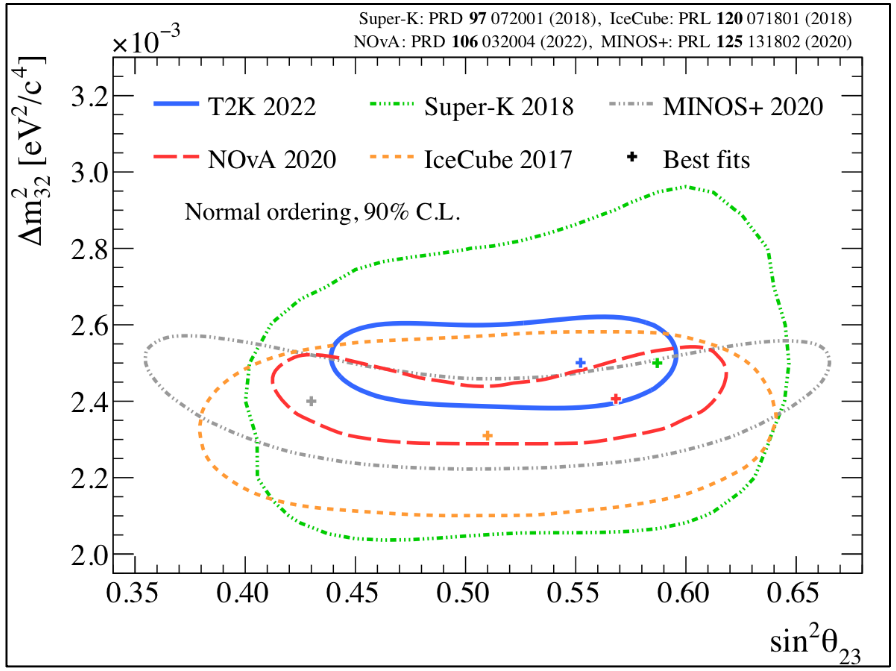
Conclusion

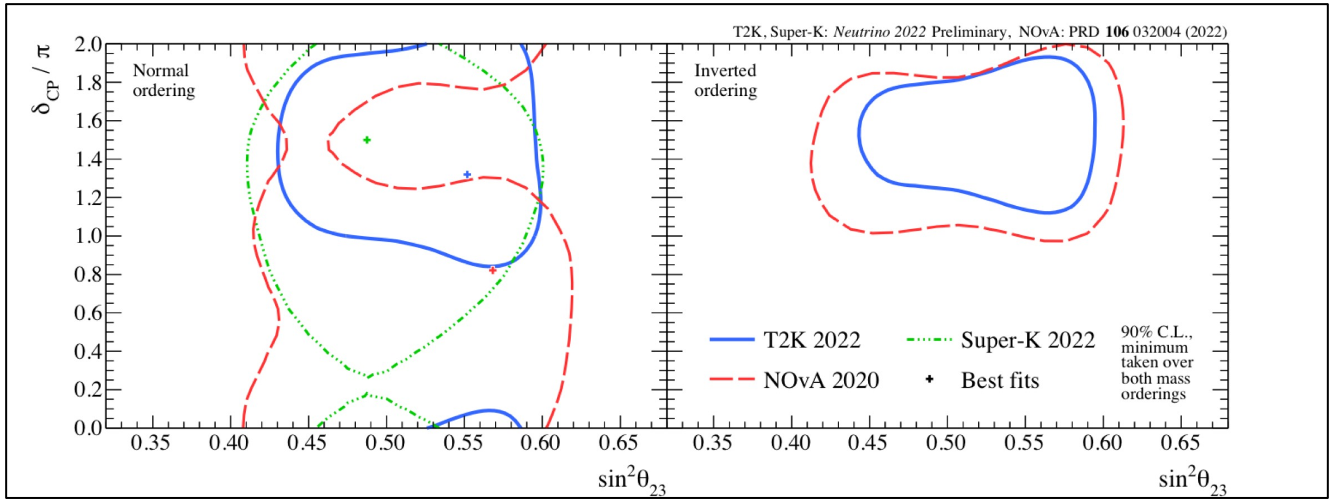
Using Hybrid-Frequentist and Bayesian analyses, T2K currently has the world-leading measurement on Δm^2_{32} and $\sin^2\theta_{23}$

Future oscillation analyses are planning to leverage new upgrades at the near and far detectors.

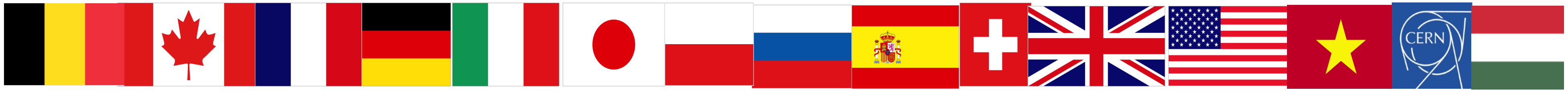
Many exciting results coming out of T2K including the results presented here.

Stay tuned for more results!





Thank you



Backup Slides

Barlow-Beeston Method

$$N_{MC,i}^{true} = \beta_i \times N_{MC,i}^{gen}$$

Barlow and Beeston methods with changes proposed by Conway allow us to rewrite the log-likelihood function for a single source as

$$-2\ln\mathcal{L}_{stat} = -2\ln\mathcal{L}_{Poisson} - 2\ln\mathcal{L}_{MC\ stat}$$

$$= 2\sum_i N_i^{MC}(\vec{\theta}) - N_i^{data} + N_i^{data}\ln\left(\frac{N_i^{data}}{N_i^{MC}(\vec{\theta})}\right) + \frac{(\beta_i - 1)^2}{2\sigma_{\beta_i}^2}$$

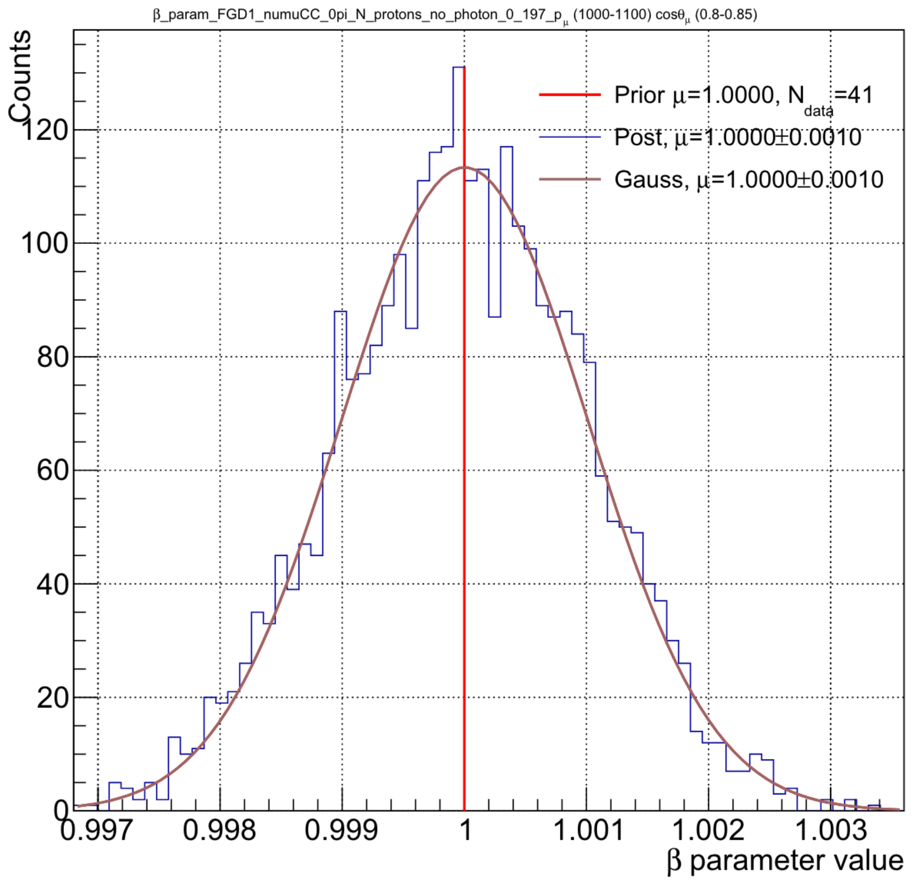
Since we only really care about total statistical uncertainty in a bin and each source's statistical uncertainty is independent, we can combine them assuming that they are Gaussian.

The mean of this distribution of β satisfies

$$\beta_i^2 + \left(N_i^{MC}\sigma_{\beta_i}^2 - 1\right)\beta_i - N_i^{data}\sigma_{\beta_i}^2 = 0.$$

Barstow and Beeston: https://doi.org/10.1016/0010-4655(93)90005-W

Conway Paper: https://doi.org/10.48550/arXiv.1103.0354



Feldman-Cousins

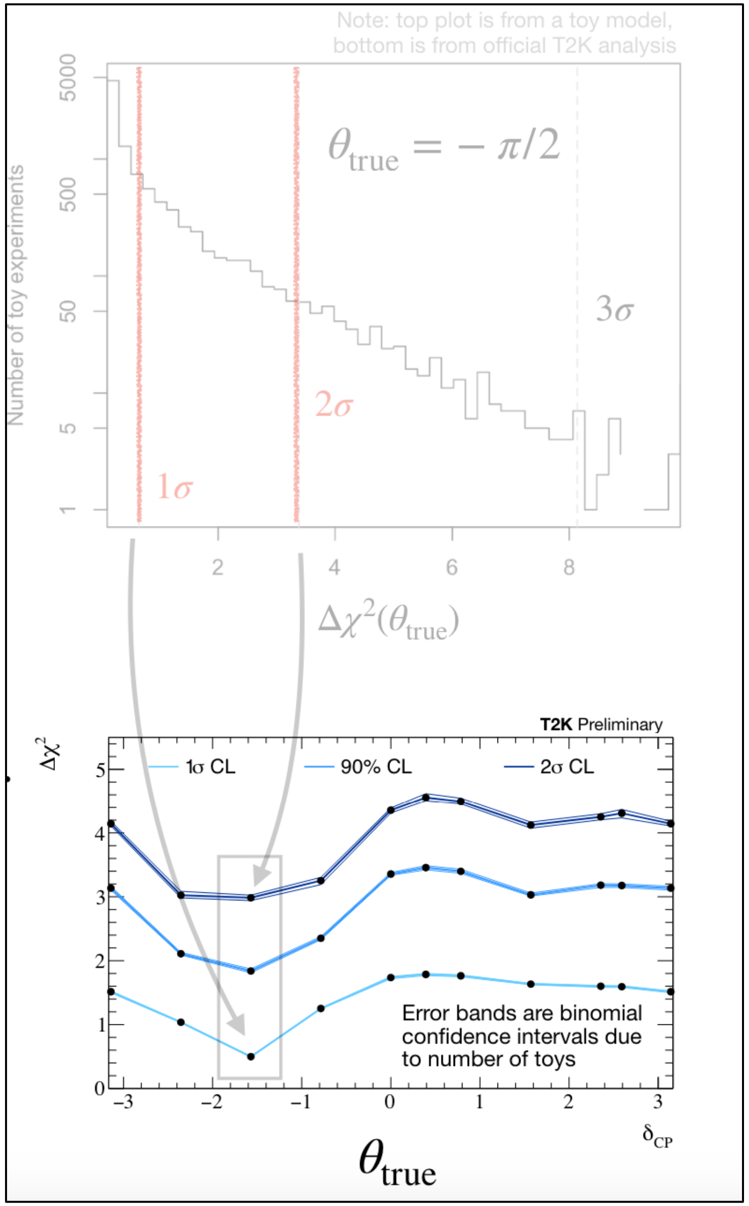
Feldman-Cousins is an algorithm for calculating confidence intervals (CIs) ensuring coverage and that physical boundaries for parameters are respected.

Generate many toy-datasets for some known value of the parameter, θ_{true}. (T2K performs this for a range of values of δ_{CP} and $\sin^2\theta_{23}$)

Compute $\Delta\chi^2(\theta_{true})$ and find its distribution

Define critical values $P(\Delta\chi^2_{true} < \Delta\chi^2_c | \theta_{true}) = 68\%, 90\%, \ldots$

Use this result to determine $\Delta\chi^2_c$ values for data-fit.



Oscillation parameters – T2K Only fit (Run 1-10)

Reactor constraint applied $sin^2 2\theta_{13} = 0.0861 \pm 0.002$

Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.66, -0.97]$	
90%	$[-3.00, -0.49]$	$[-1.79, -1.09]$
2σ	$[-\pi, -0.26] \cup [3.11, \pi]$	$[-2.20, -0.75]$
3σ	$[-\pi, 0.32] \cup [2.63, \pi]$	$[-2.82, -0.14]$

Feldman-Cousins CL from Hybrid-Frequentist analysis for δ_{CP}

Confidence level	Interval (NH)	Interval (IH)
1σ	$[0.528, 0.582]$	
90%	$[0.443, 0.592]$	$[0.537, 0.584]$
2σ	$[0.436, 0.597]$	$[0.505, 0.593]$

Feldman-Cousins CL from Hybrid-Frequentist analysis for $\sin^2(\theta_{23})$

	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})\text{eV}^2$
2D best fit	0.531	2.51
68% C.I. (1σ) range	0.489 – 0.560	-2.56 – -2.53 $\cup$ 2.42 – 2.58
90% C.I. range	0.466 – 0.571	-2.61 – -2.48 $\cup$ 2.39 – 2.60
95.4% (2σ) C.I. range	0.455 – 0.579	-2.63 – -2.45 $\cup$ 2.38 – 2.62
99.73% (3σ) C.I. range	0.436 – 0.598	-2.70 – -2.39 $\cup$ 2.33 – 2.67

Credible intervals from the Bayesian analysis for disappearance parameters

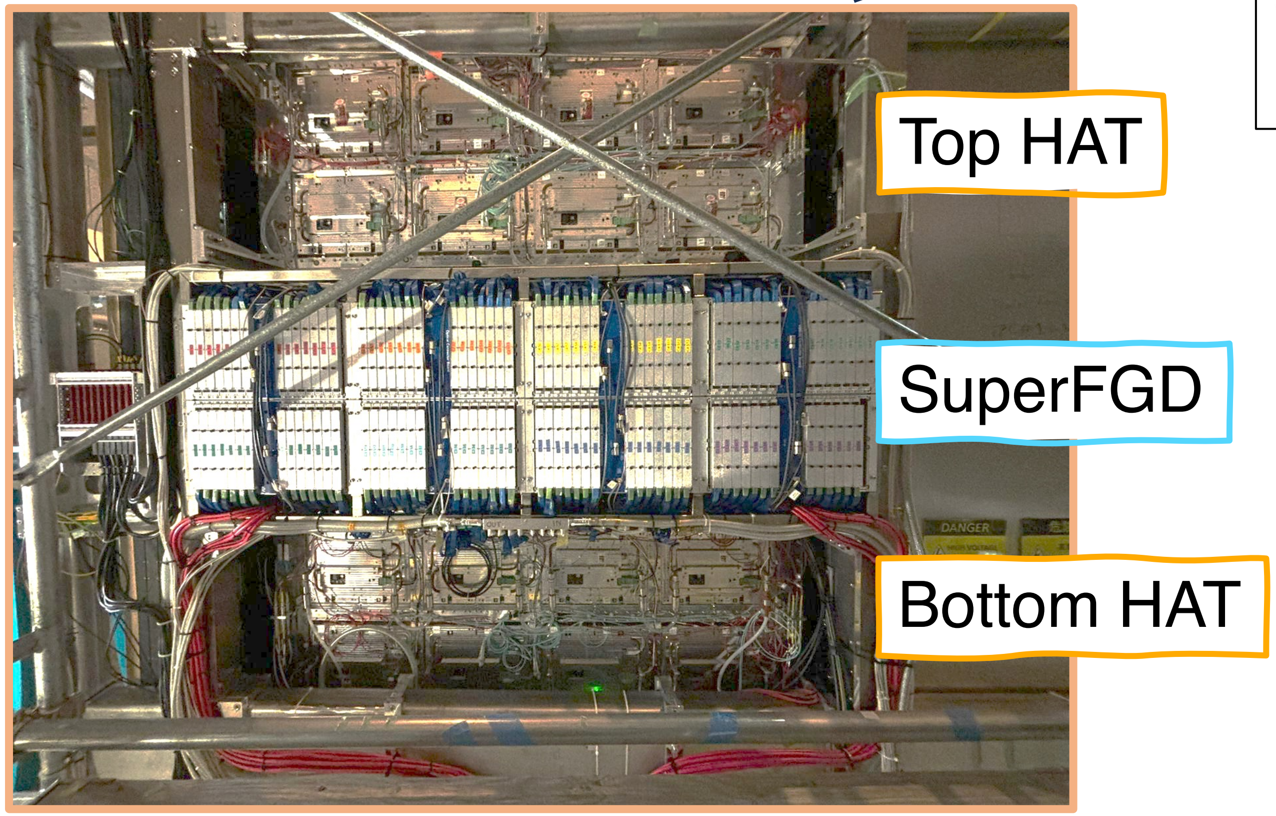
	$\sin^2\theta_{13}$	δ_{CP}
2D best fit	0.0221	-1.84
68% C.I. (1σ) range	0.0214 – 0.0227	-2.58 – -1.01
90% C.I. range	0.0210 – 0.0232	-3.02 – -0.50
95.4% (2σ) C.I. range	0.0207 – 0.0234	$-\pi$ – -0.25 & 3.08 - π
99.73% (3σ) C.I. range	0.0200 – 0.0241	$-\pi$ – 0.50 & 2.39 – π

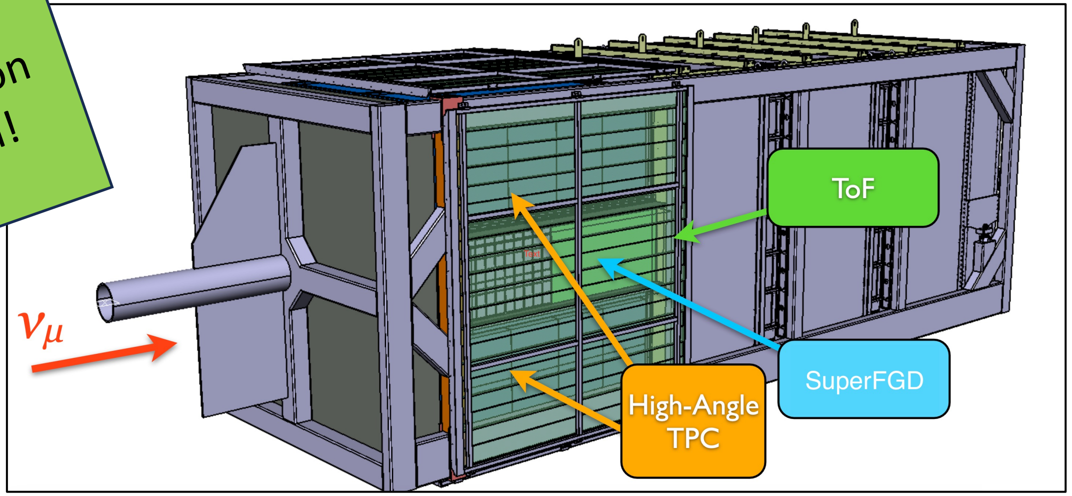
Credible intervals from the Bayesian analysis for appearance parameters

ND Upgrade

See Eric Chong's talk on Thursday afternoon!

Photo taken April 18, 2024

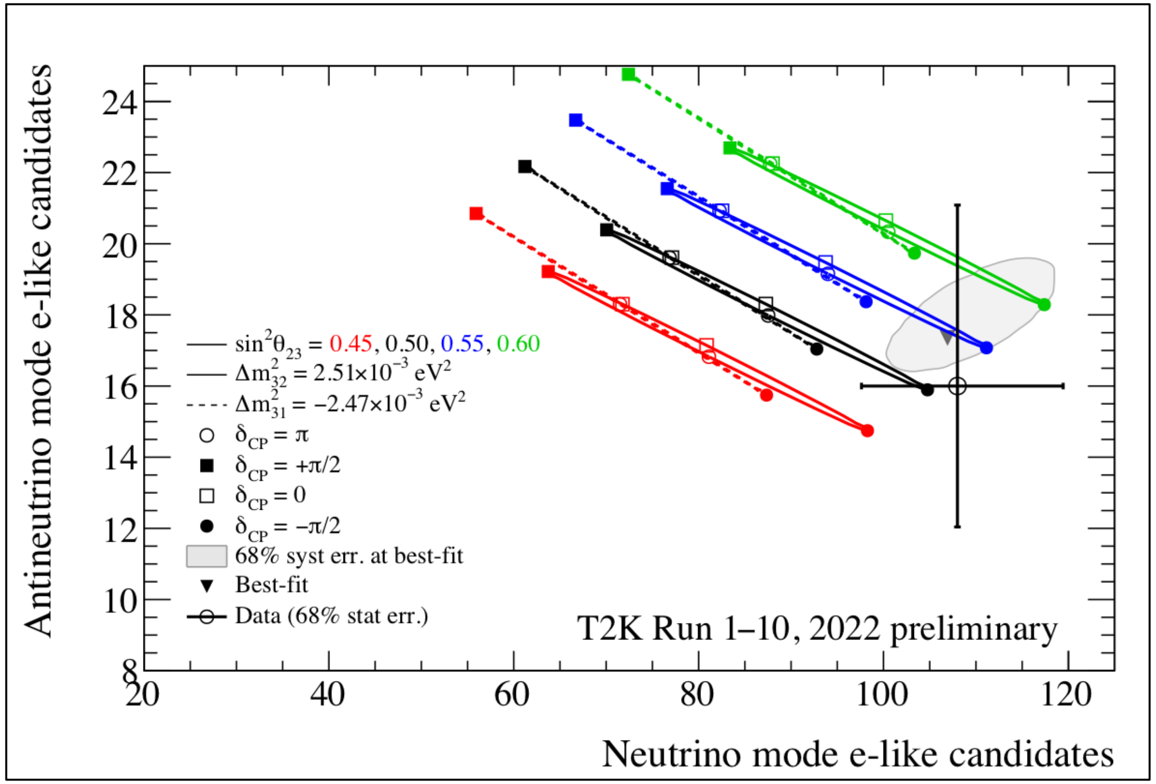


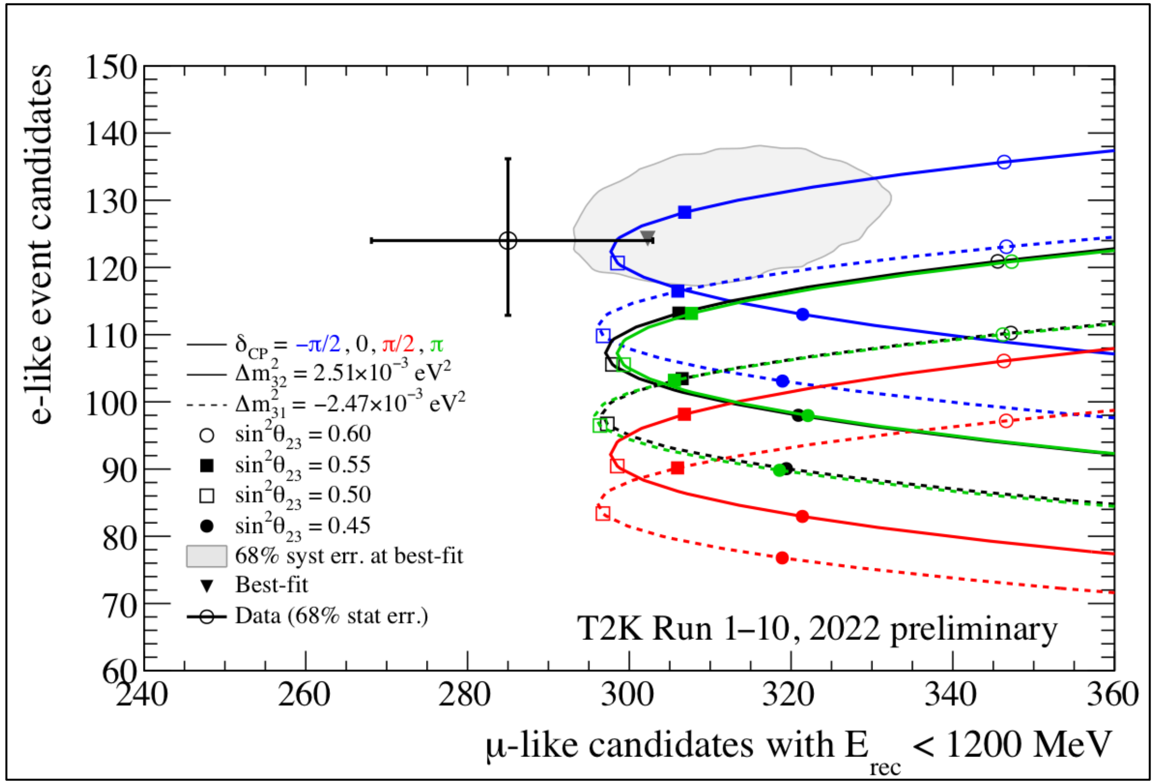


Recent upgrades to ND280 have replaced the P0D detector with 3 new types of detectors to improve

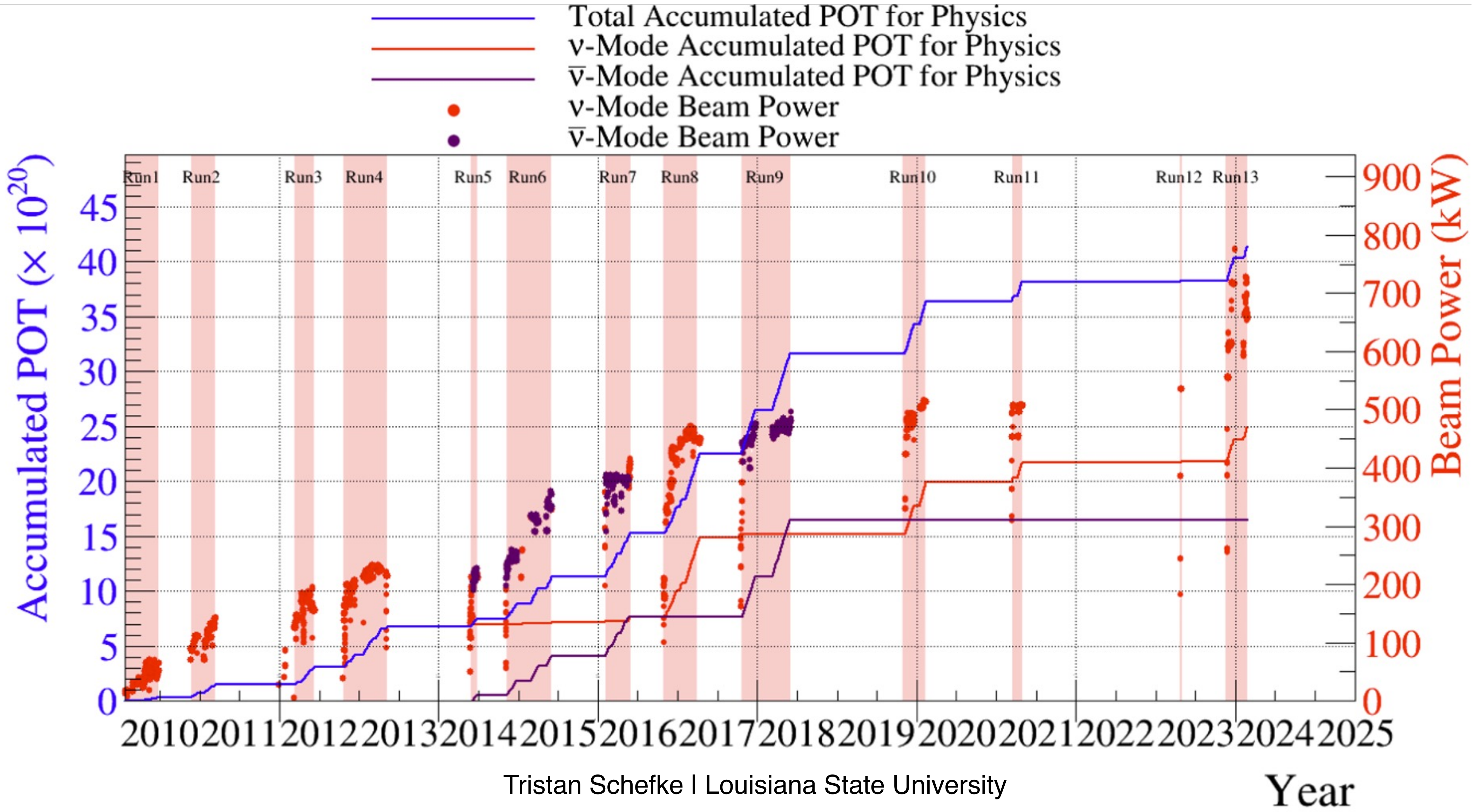
- Increase acceptance of high-angle scattered leptons from ν_μ/ $\bar{\nu}_\mu$interactions
- Ability to reconstruct protons < 300 MeV/c
- Reconstruct neutron kinematics on an event-by-event basis.

Bi-event Probability Plots

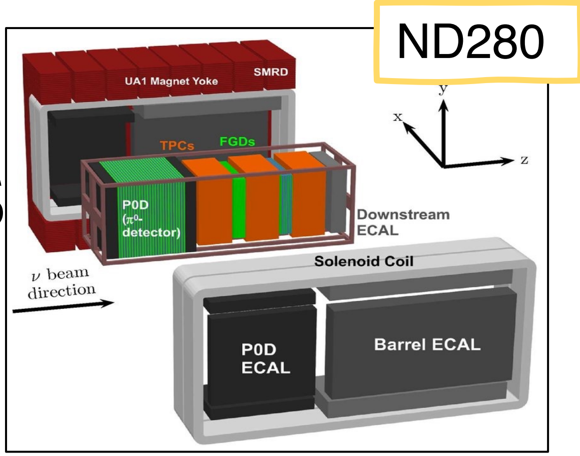


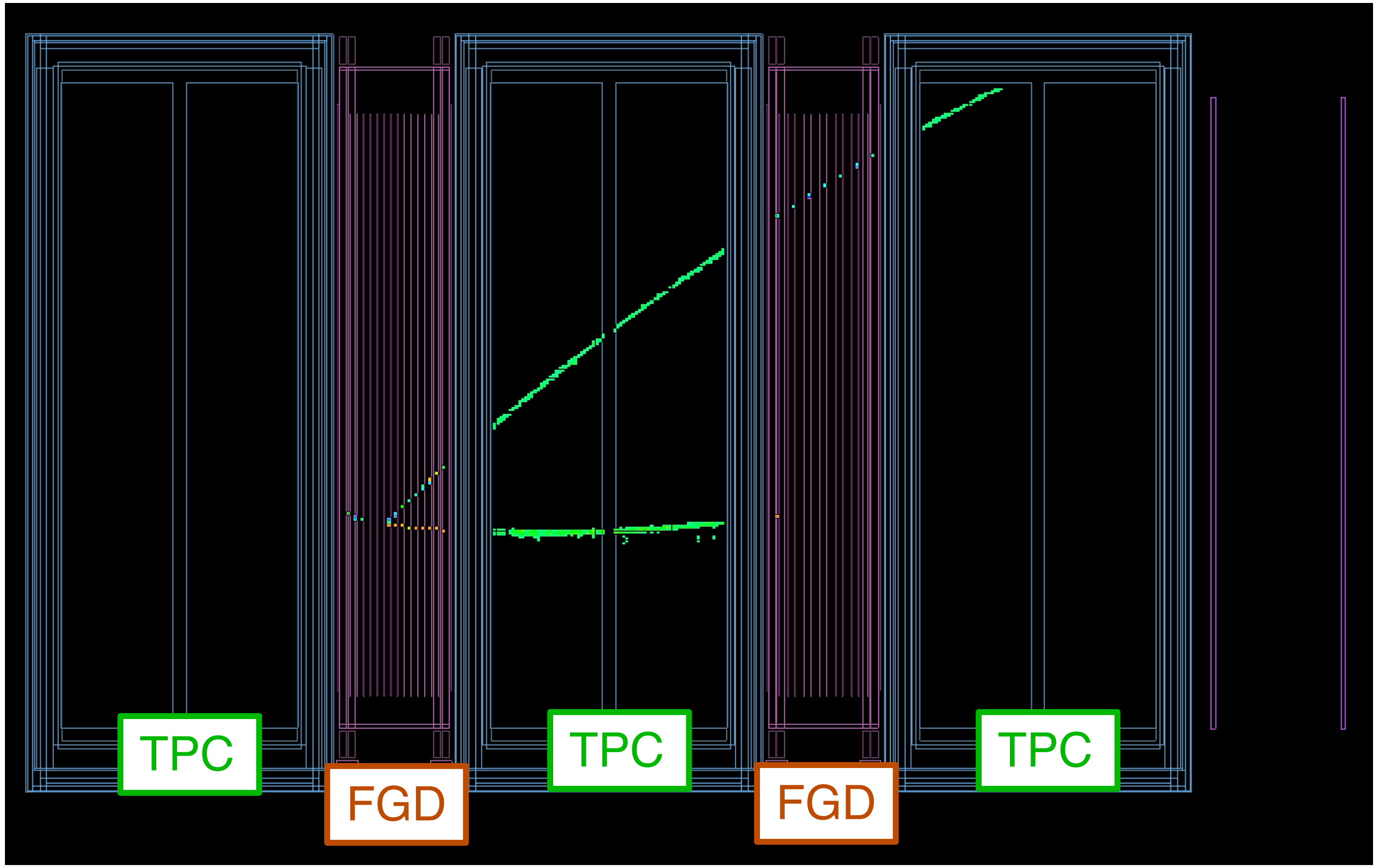


Accumulated POT



Example of ND280 Event Displays





CC0π interaction