Neutrino Oscillation Measurements at T2K

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NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

T2K

Outline

- T2K Experiment
  - Flux Model
  - Interaction Model
  - Near Detector samples
  - Far Detector samples
- Analysis flow
- New Results
  - Atmospheric parameters
  - CP parameters
  - Jarlskog Invariant
- Joint Fits

Questions in Neutrino Oscillation Physics

- CP violation → different $\nu/\bar{\nu}$ oscillation probabilities

Appearance channel

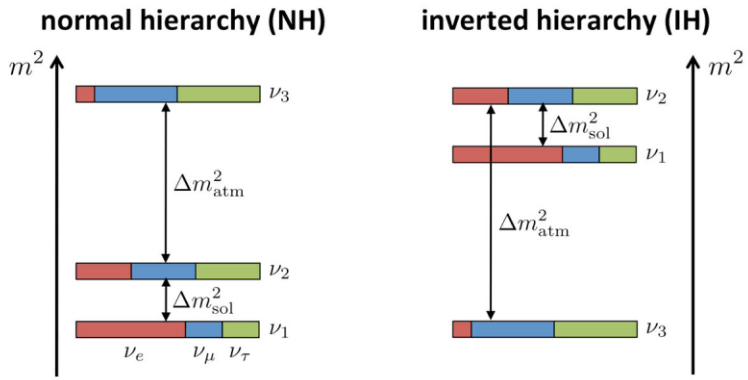
$$\begin{matrix} P(\nu_\mu \to \nu_e) \\ P(\bar{\nu}_\mu \to \bar{\nu}_e) \end{matrix} \approx \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right) \mp \frac{1.27\Delta m^2_{21} L}{E} 8 J_{CP} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

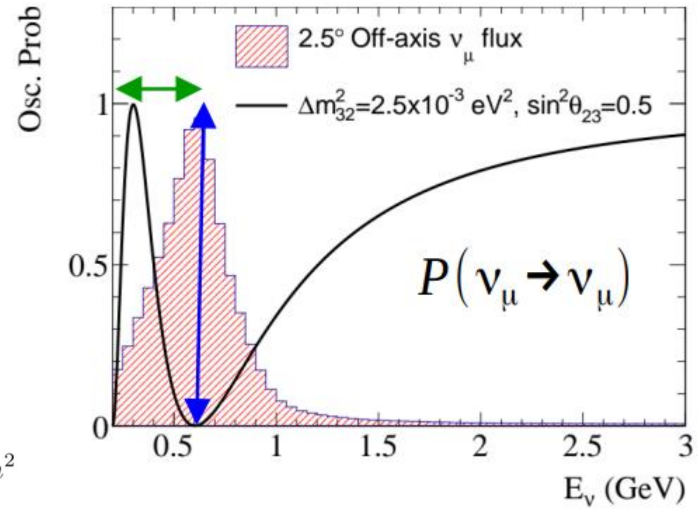
Jarlskog Invariant $J_{CP} \approx 0.033 \sin(\delta_{CP})$

- Octant of θ_{23}

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

- Mass ordering

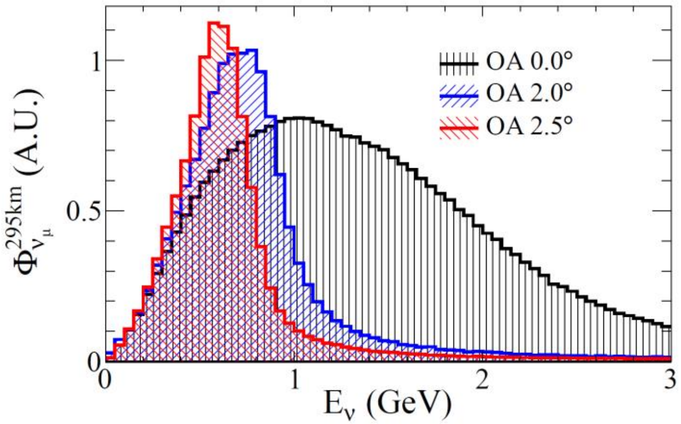


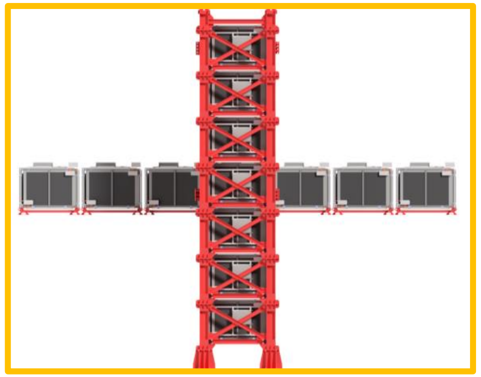


T2K Experiment

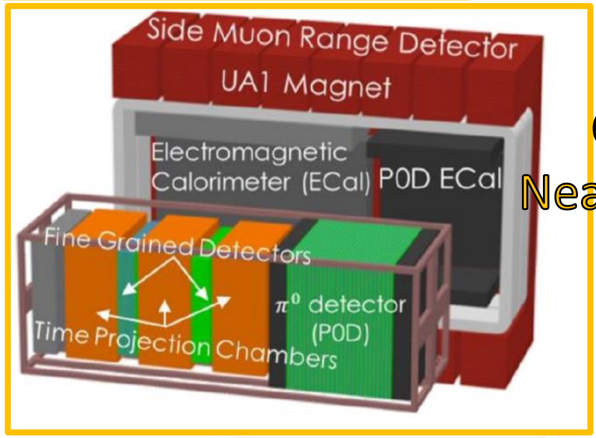
- Baseline: 295 km
- Off-axis beam
- Near Detector: ND280
- Far Detector: Super-Kamiokande

- Neutrino nucleus cross-section measurements, see **Greg's** talk in one hour
- Oscillation measurements, this talk ☺

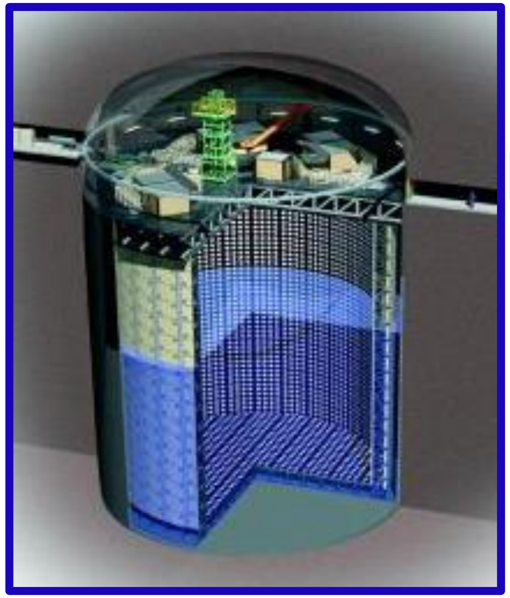


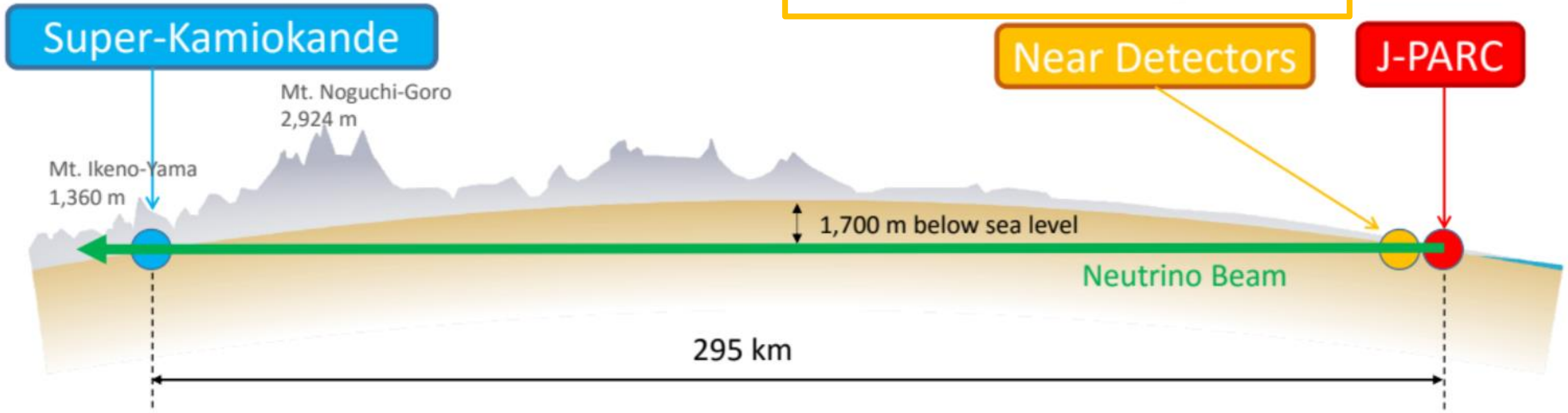


On-axis
Near Detector
INGRID



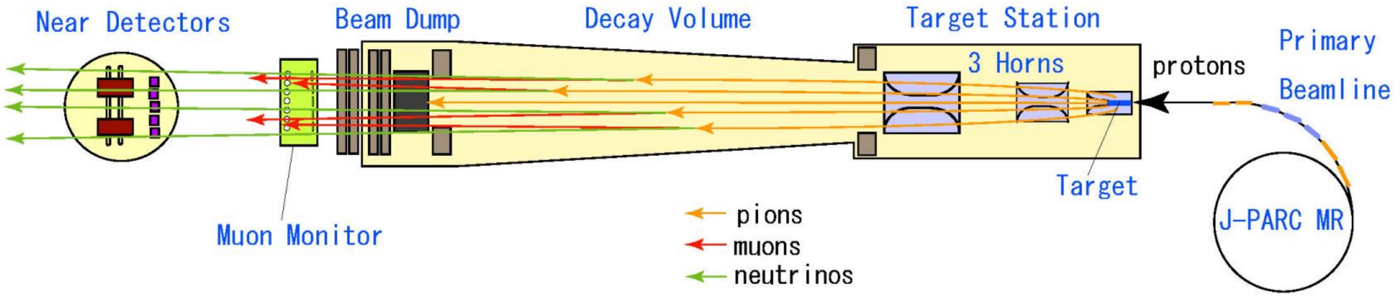
Off-axis
Near Detector
ND280





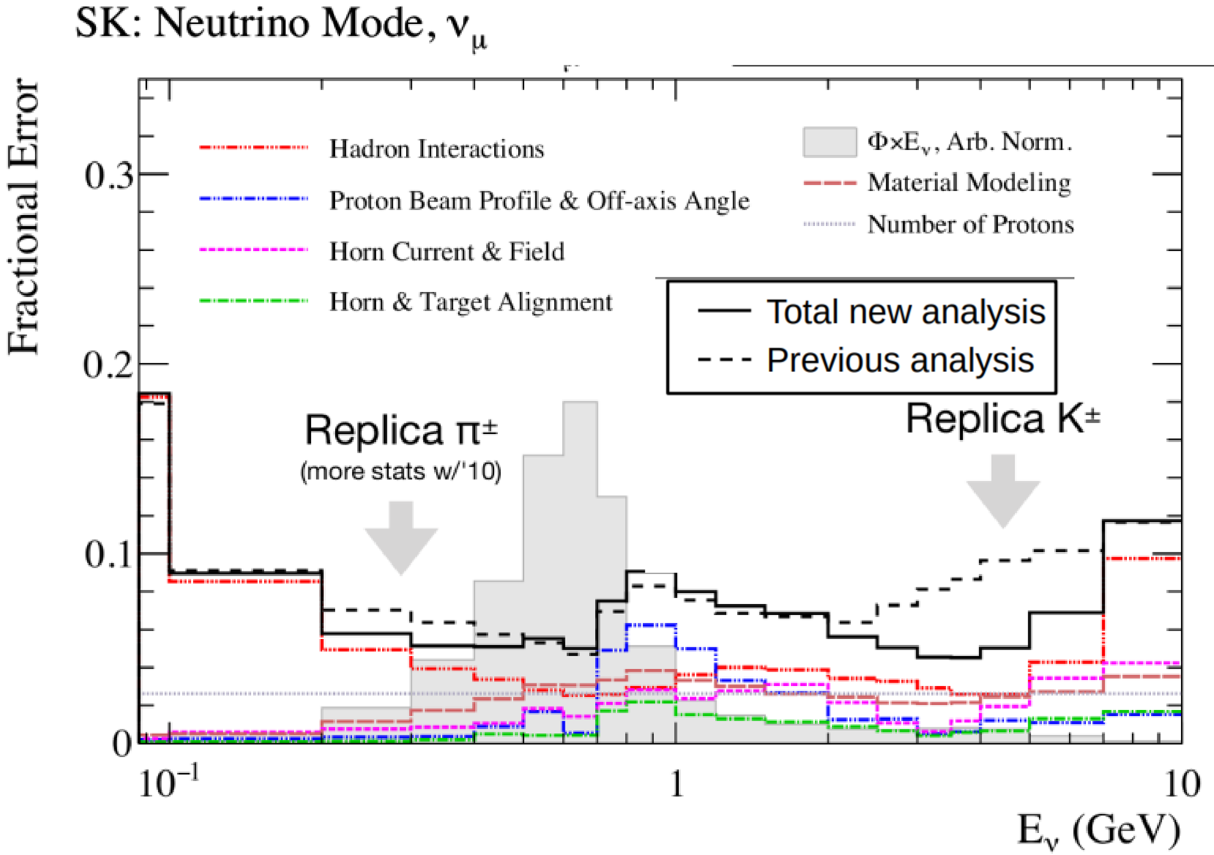
T2K Beam Production and Flux Predictions

- Protons hit graphite and hadrons (π, K) which are focused and then decay into neutrinos
- Can select $\nu/\bar{\nu}$ beam mode based on horn polarity



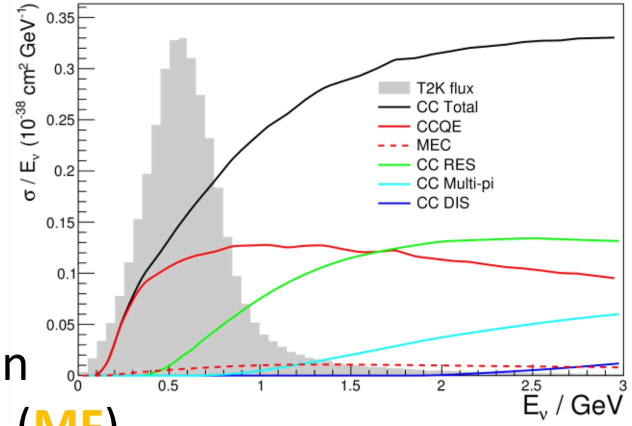
Dominant **flux** uncertainty: hadron production in collisions of protons on graphite target

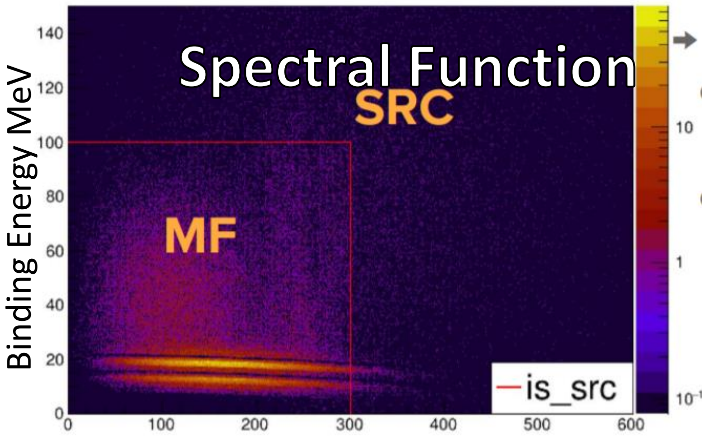
- Simulation tuned based on hadron multiplicity measurements by **NA61/SHINE**
- Moved from using **2009** **T2K replica** target data* to 2010 one**:
  - more statistics for $\pi^{\pm}$ production
  - adds $K^{\pm}$ and proton data



* Eur. Phys. J. C76, 617 (2016)
**Eur. Phys. J. C79, 100 (2019)

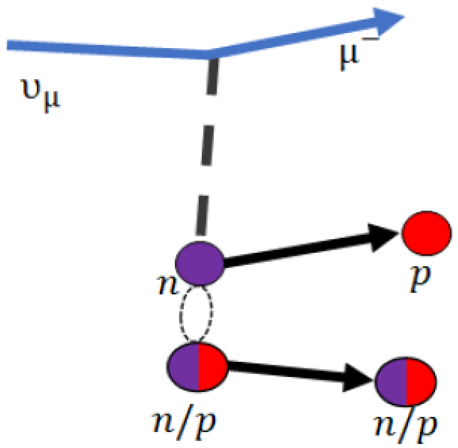
CCQE is a dominant reaction for T2K energies





Charge Current Quasi Elastic (**CCQE**)

- Expanded parameterization of the spectral function
- Normalization of each nuclear shell for Mean Field (**MF**)
- Normalization of Short Range Correlations (**SRC**)
- Added Pauli Blocking to give more freedom in low Q^2 region



2p2h/MEC

- Better description of 2p2h pn/nn pairs contribution

Other

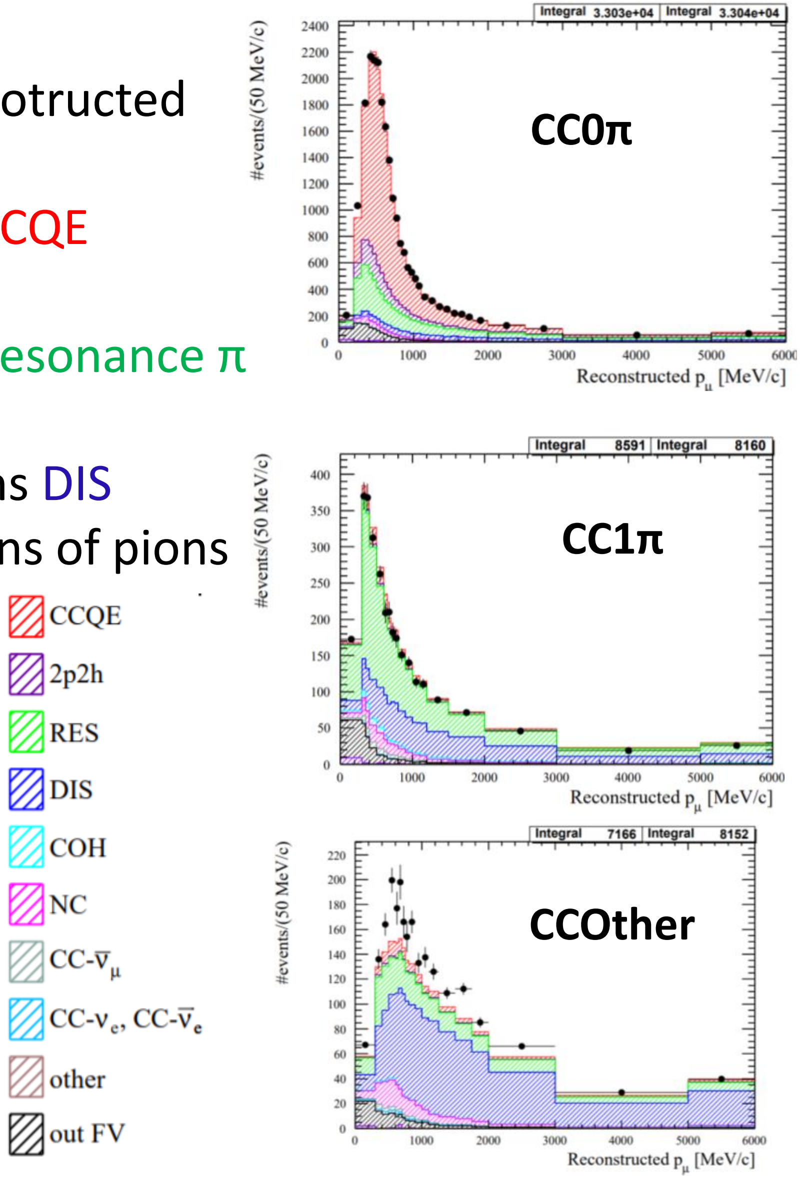
- New tune of bubble chamber data to resonance model parameters
- New resonance decay uncertainties
- Effective inclusion of binding energy for Resonant channel
- New Nucleon Final State Interactions (FSI) uncertainty
- New multi-π uncertainty varying shape of hadronic mass and π multiplicity

Old ND Samples

ND280 used to constrain cross-section and flux models.
Samples based on reconsotructed topology:
CC0π mostly constrains CCQE
μ^- and no pions
CC1π mostly constrains Resonance π production**;** μ^- and π^+
CCOther mostly constrains DIS
μ^- and other combinations of pions

Furthermore, each sample has different kinematic properties.

2020 Samples



New samples at the near detector

This year we add new information to the fit thanks to photon and proton tagged samples.

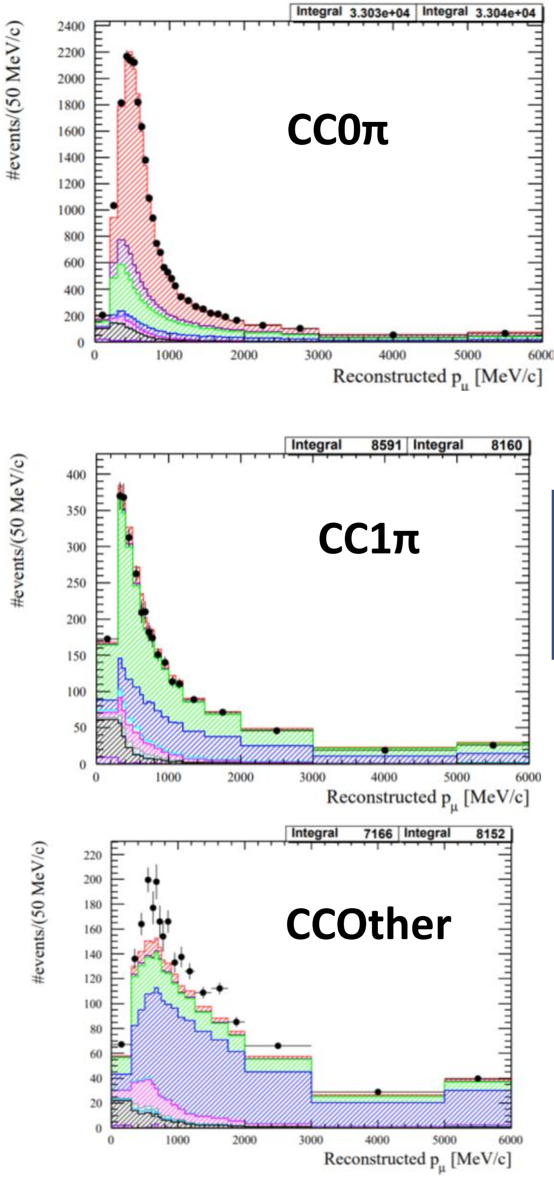
- **proton and photon samples** help better probe new model.

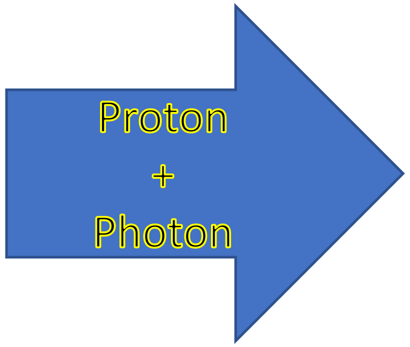
$\bar{\nu}$ beam mode samples remains the same.

Analogous set of Samples for FGD1 and FGD2 subdetectors.

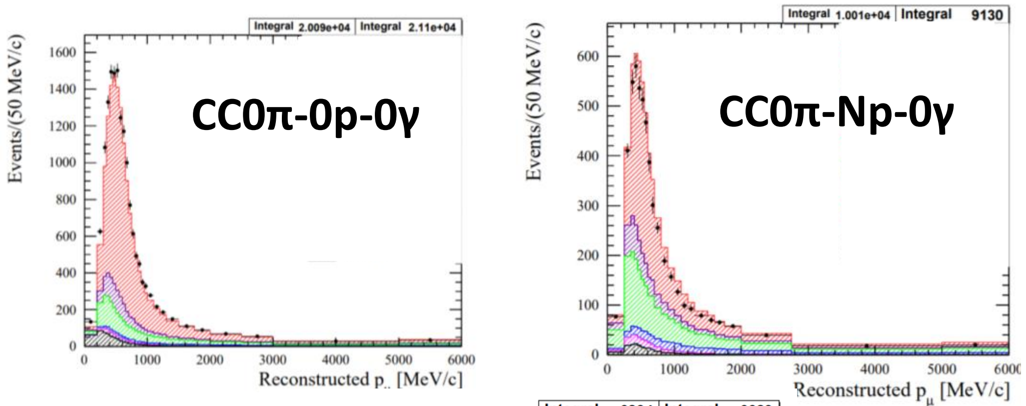
Total number of ND samples 18→22

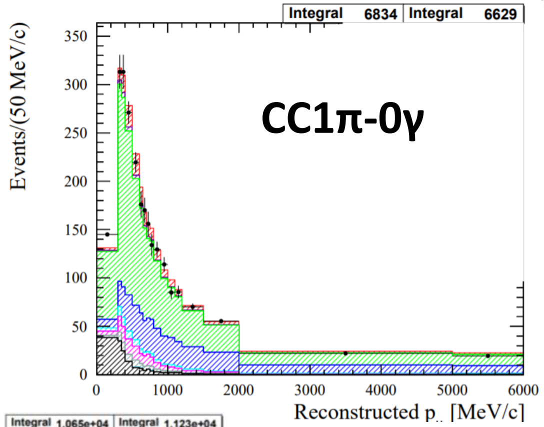
2020 Samples

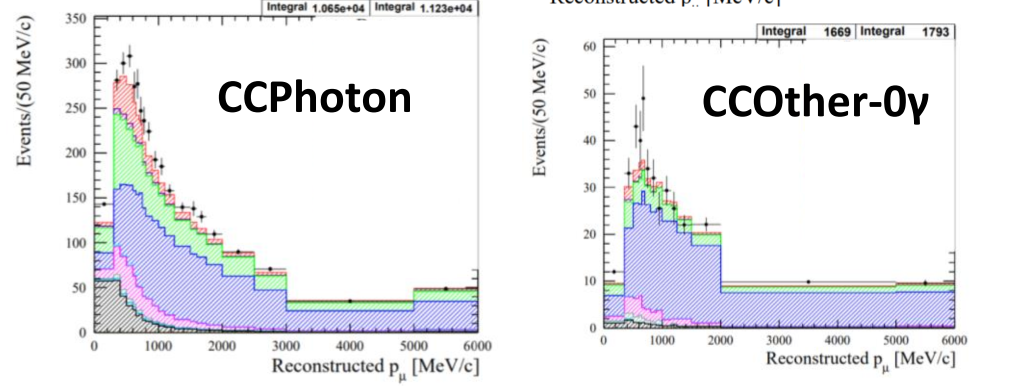




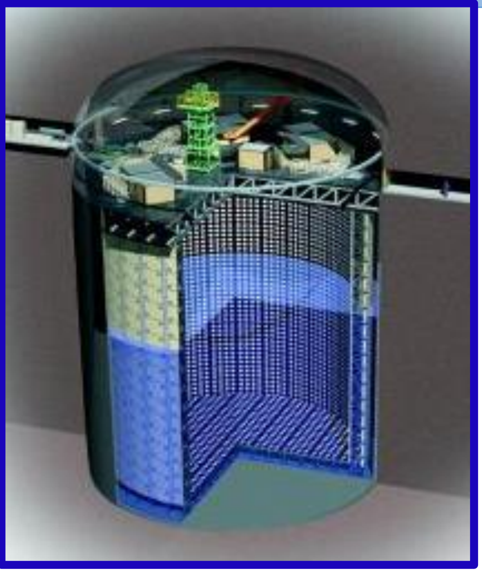
2022 Samples



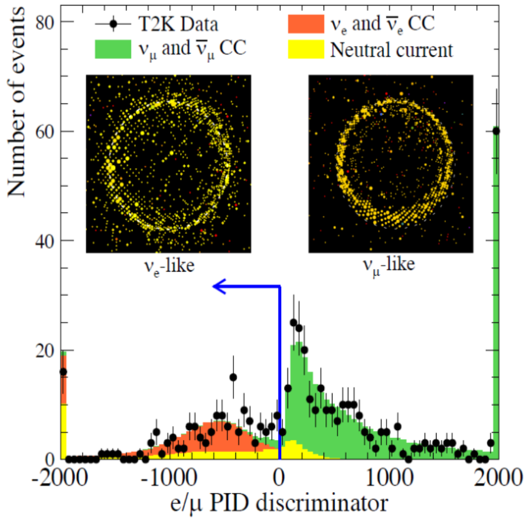




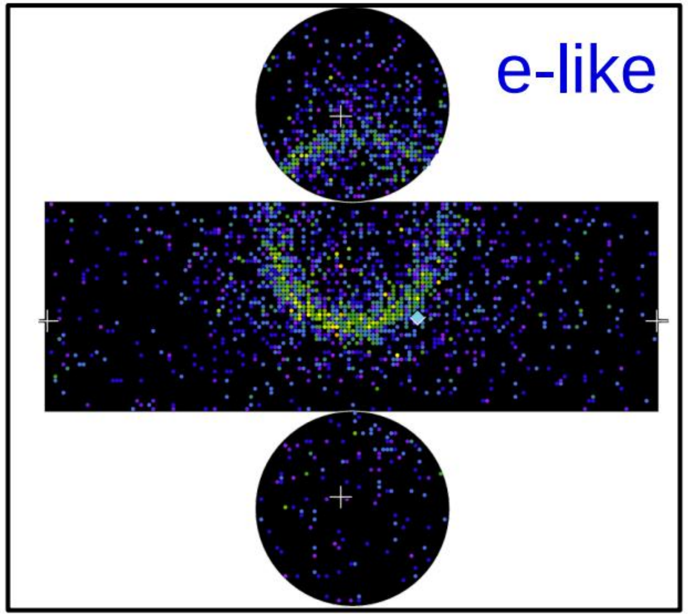
Far Detector Sample

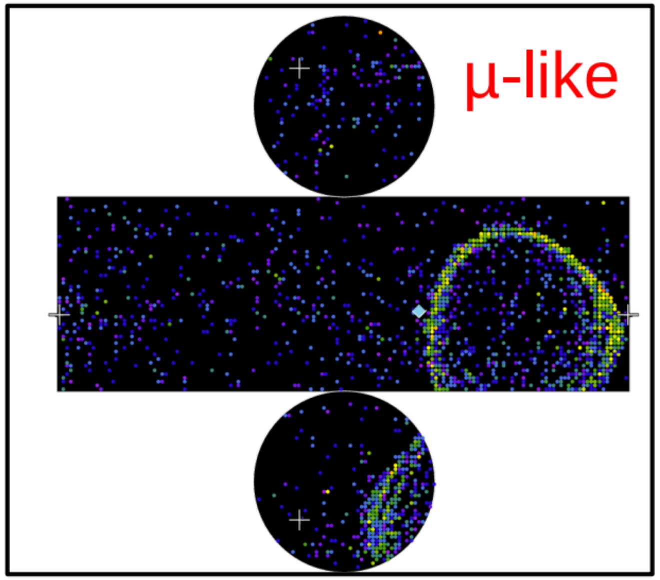


- Good separation between μ and e, based on ring shape
- $\nu/\bar{\nu}$ mode depending on horn polarity
- Selection based on ring type and beam mode



Mode	Sample Name	Description
$\boldsymbol{\nu}$	**1Re**	One e-like ring in $\boldsymbol{\nu}$ mode
	1Re CC1π+	One e-like ring and Michel electron in $\boldsymbol{\nu}$ mode
	1Rμ	One μ-like ring in $\boldsymbol{\nu}$ mode
	MRμ CC1π+ (Multi-Ring)	New! (next slide)
$\bar{\boldsymbol{\nu}}$	**1Re**	One e-like ring in $\bar{\boldsymbol{\nu}}$ mode
	1Rμ	One μ-like ring in $\bar{\boldsymbol{\nu}}$ mode



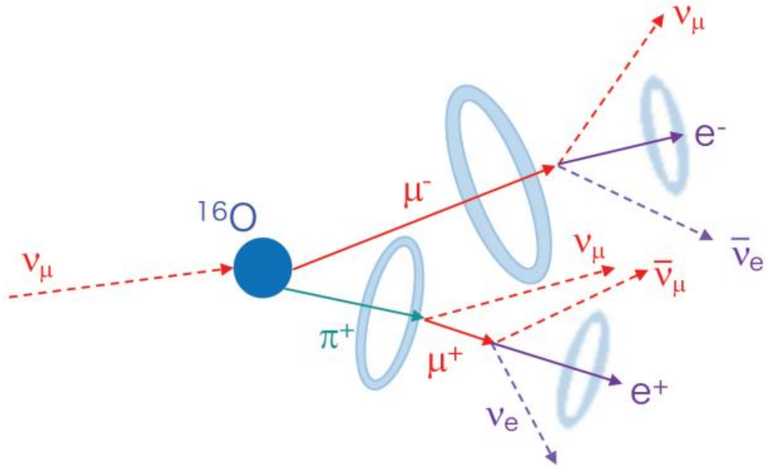


Multi-Ring

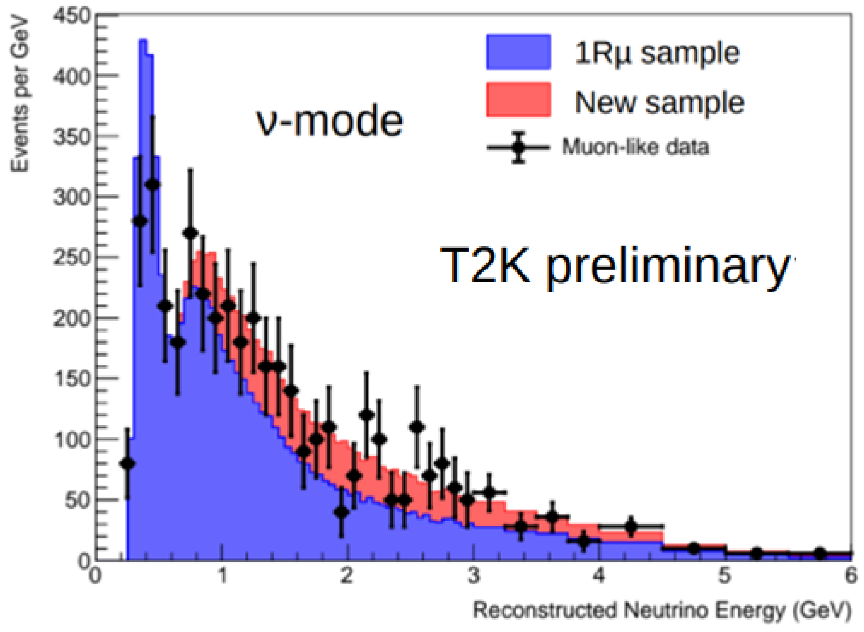
MRμ CC1π^+:

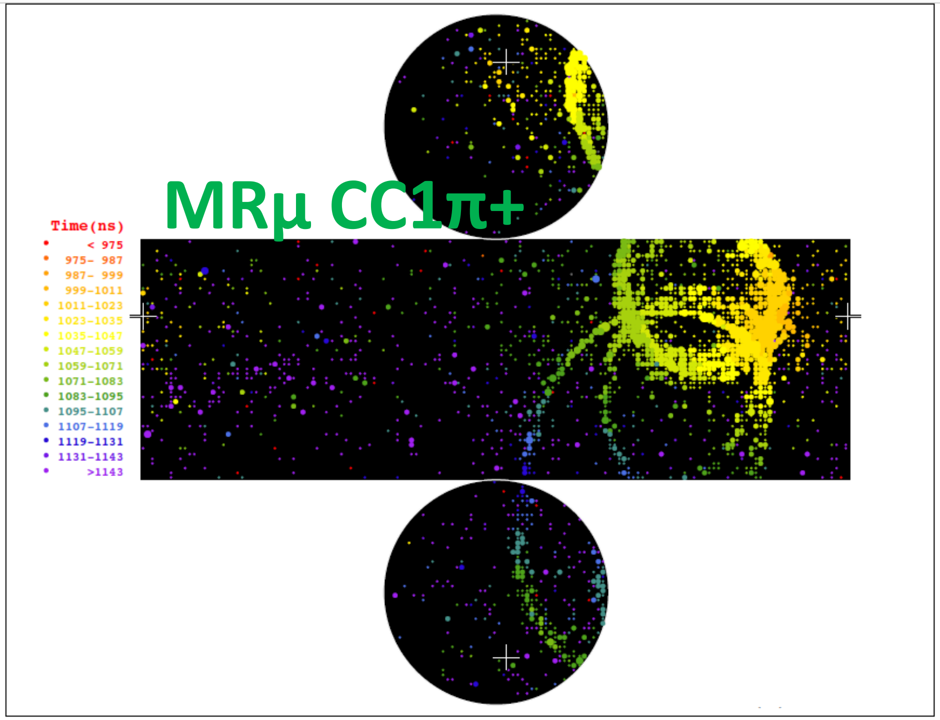
- Two rings (1 μ^- and 1π^+) and Michel electron (from 1μ^-) or
- One 1μ^- ring and 2 Michel electrons (from 1π^+)

- Targeting ν_μ CC1π^+ interactions in ν-mode
- Increase ν-mode μ-like statistics by ~30%
- Sensitive to oscillations, higher energy than nominal μ-like sample helps crosscheck model is well under control.



See T2K poster: 410





Oscillation Analyses

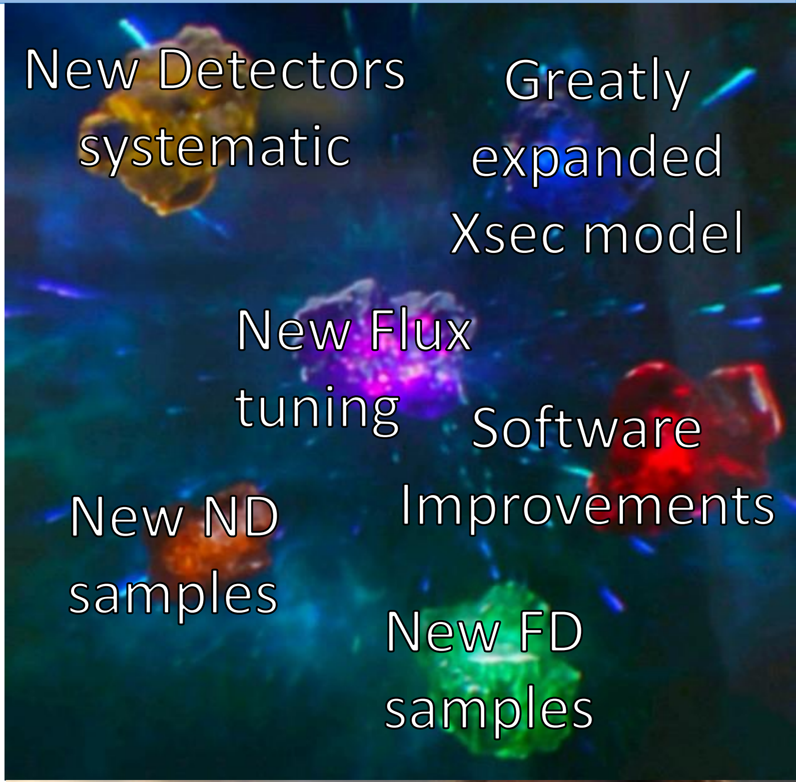
T2K uses two analysis frameworks using Poisson likelihood ($-\boldsymbol{logL}$) and gaussian penalty terms from our priors. ND additionally used MC statistical uncertainty following Barlow-Beeston* approach.

- **Consecutive** ND+FD fit and **Frequentist** Approach

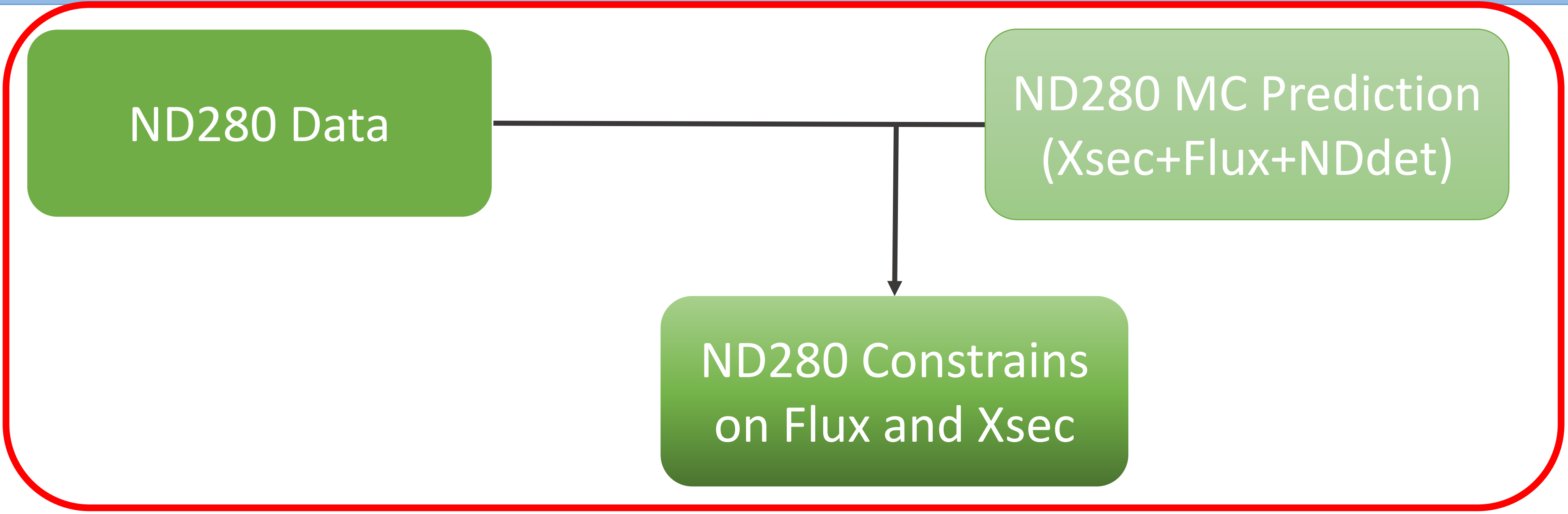
- **Simultaneous** ND+FD fit and **Bayesian** Approach

- Both have same samples and model
- Fit is performed with and without reactor constraints (RC), here we show only with RC. RC applied to $\sin\theta_{13}$

*Comput. Phys. Commun. (1993)

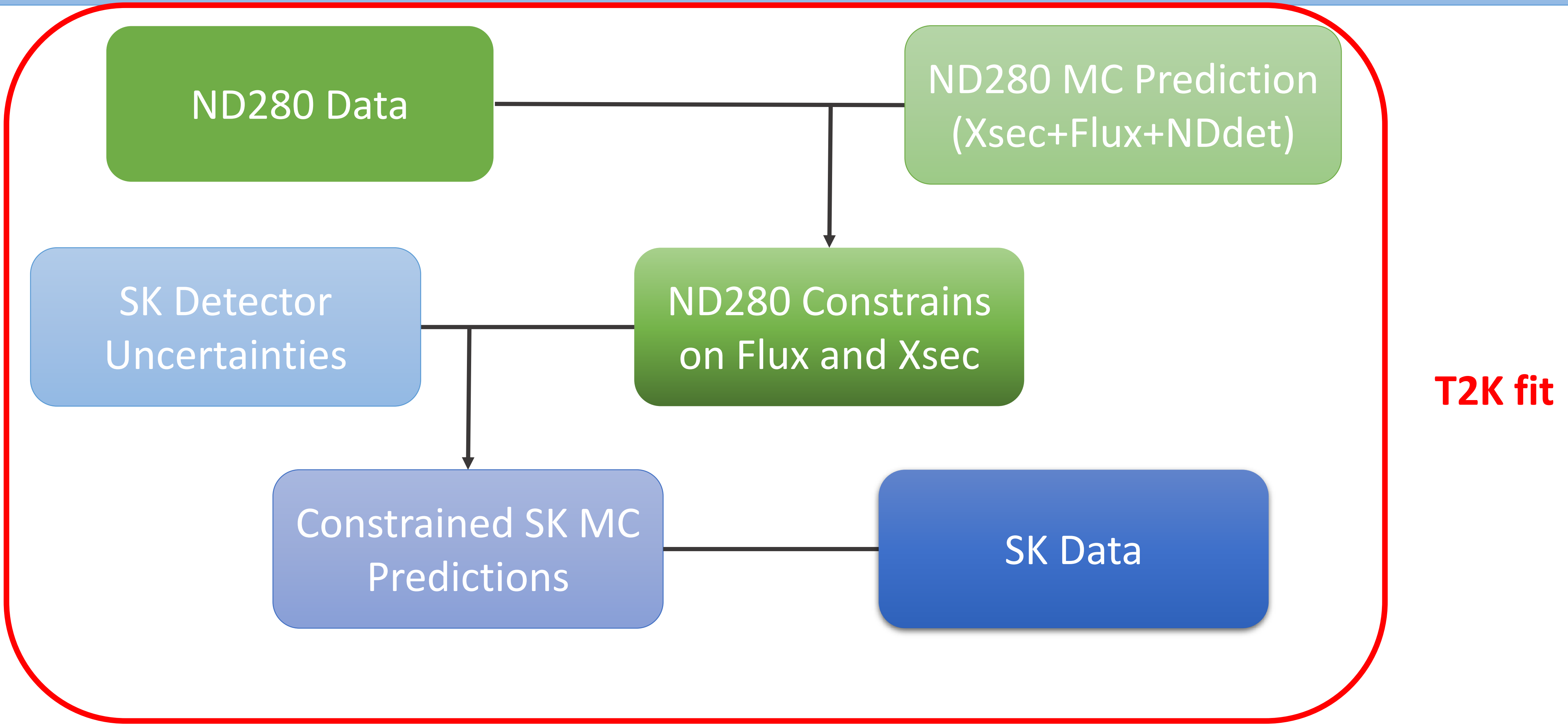


Consecutive ND+FD and Frequentist Approach

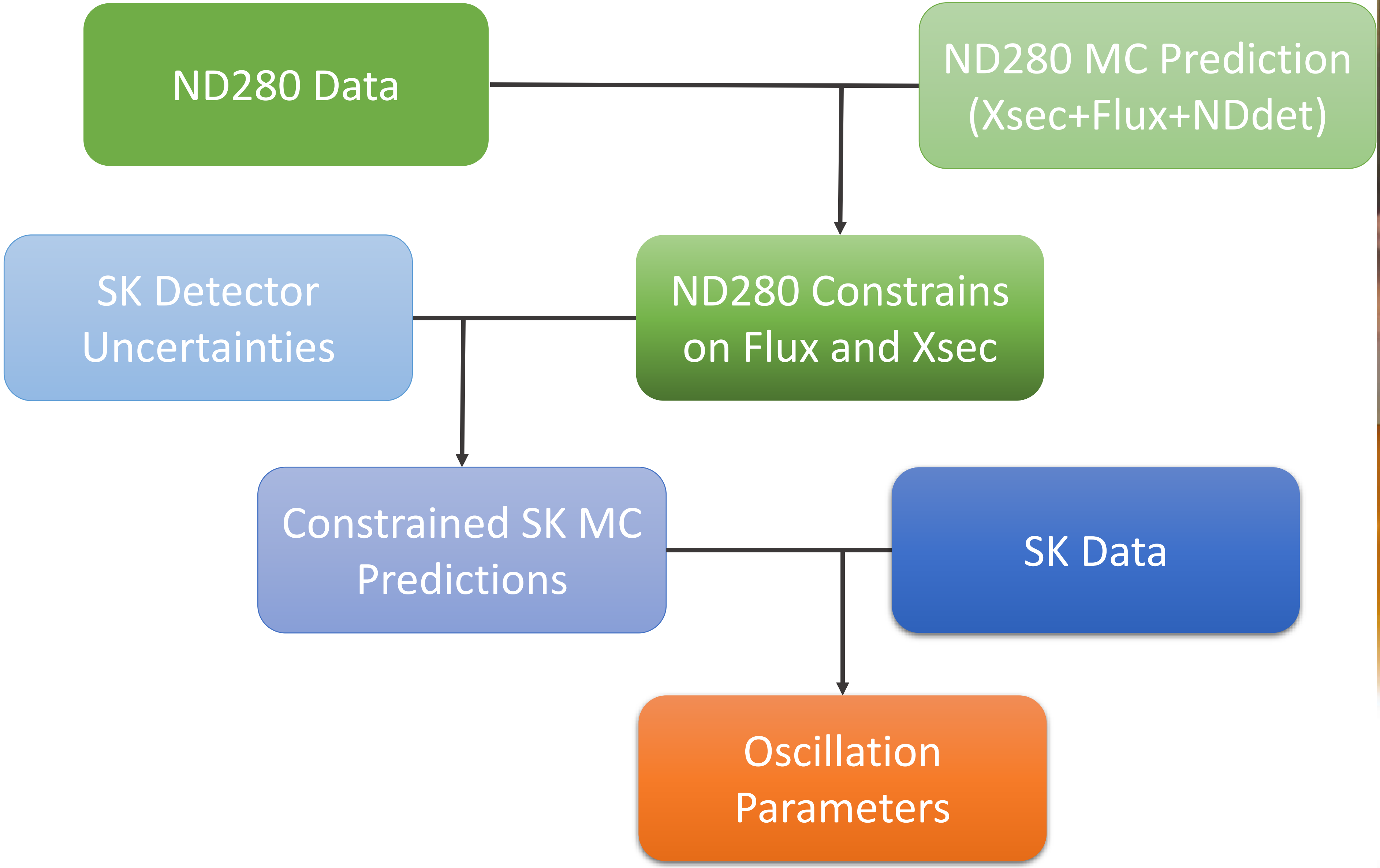


ND280 fit

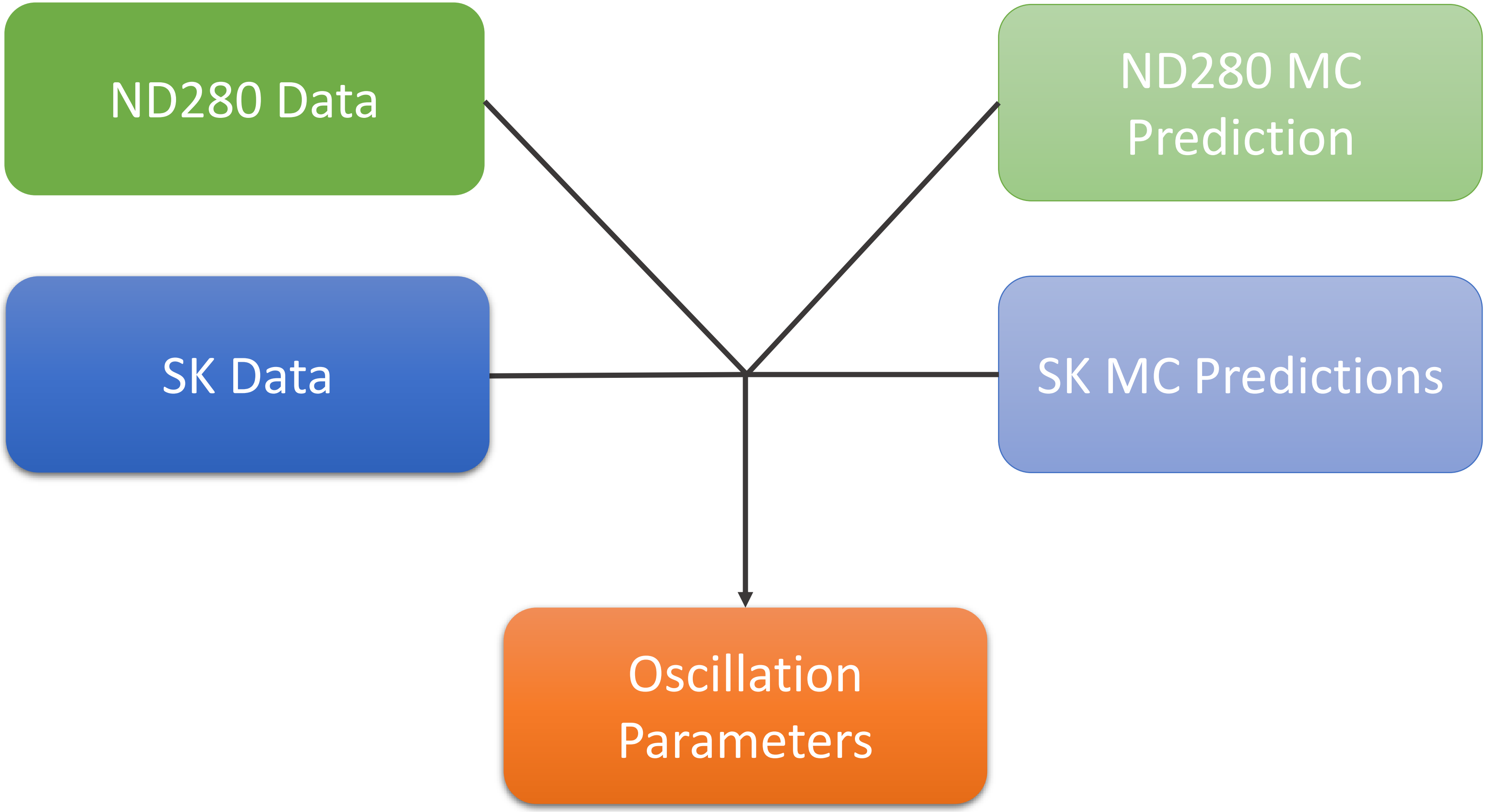
Consecutive ND+FD and Frequentist Approach



Consecutive ND+FD and Frequentist Approach



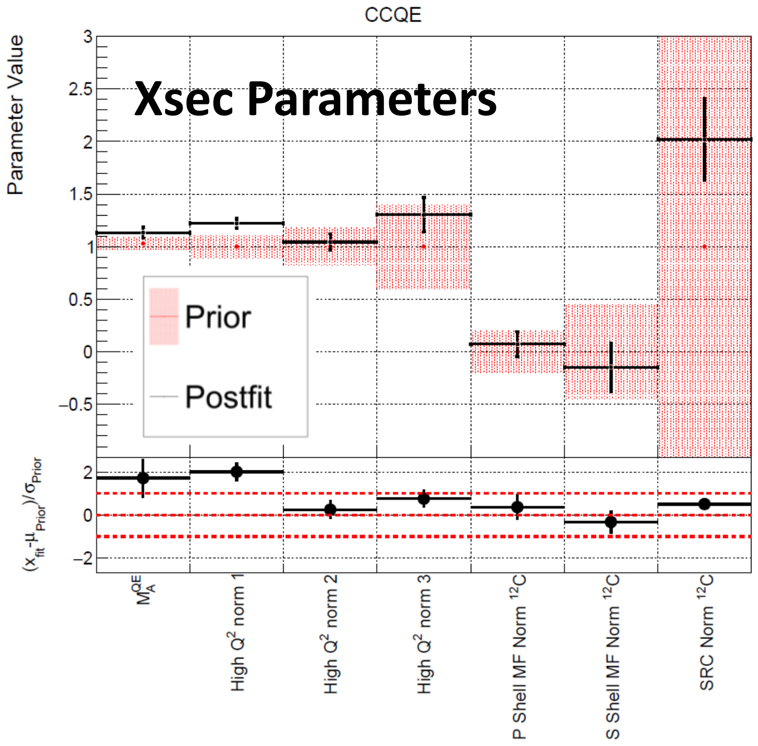
Simultaneous ND+FD and Bayesian Approach

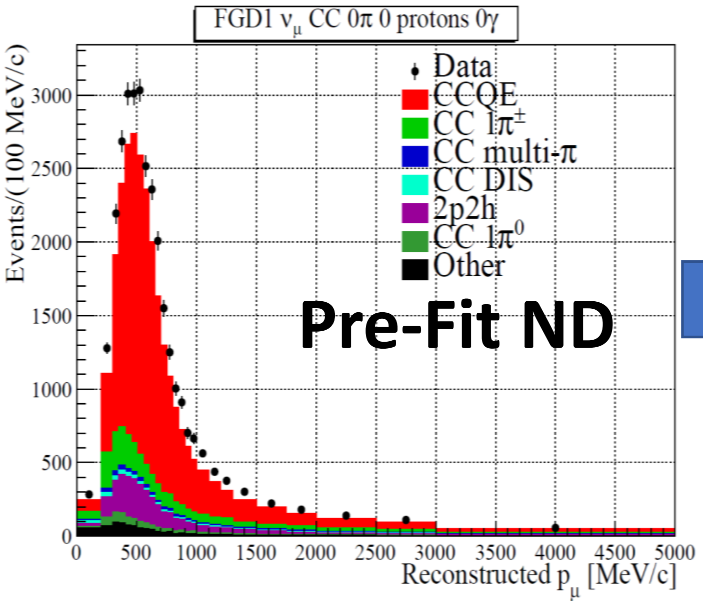


ND Fit Results

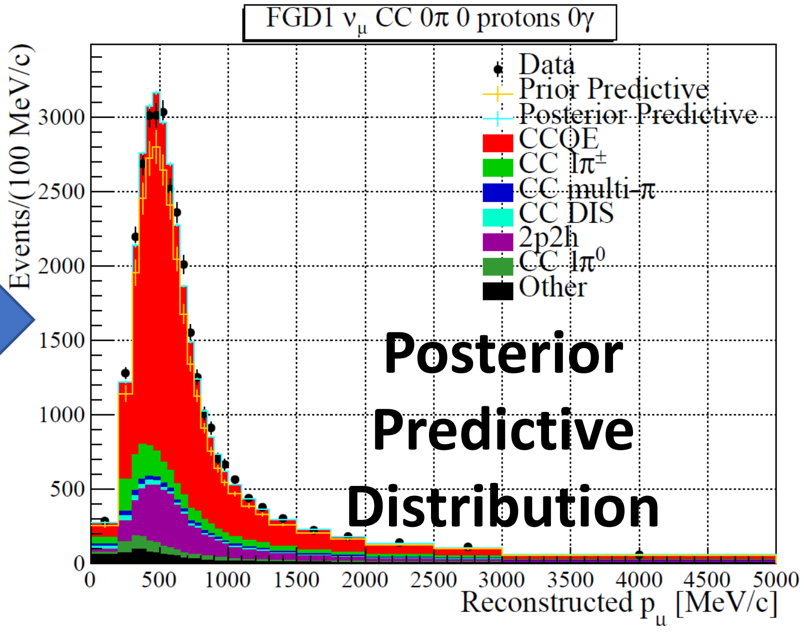
ND280 data crucial to tune the prior model and shrink the uncertainties

Cross-section parameters are getting pulled to accommodate for nominal disagreement.
See T2K poster: 1225





Data Fit



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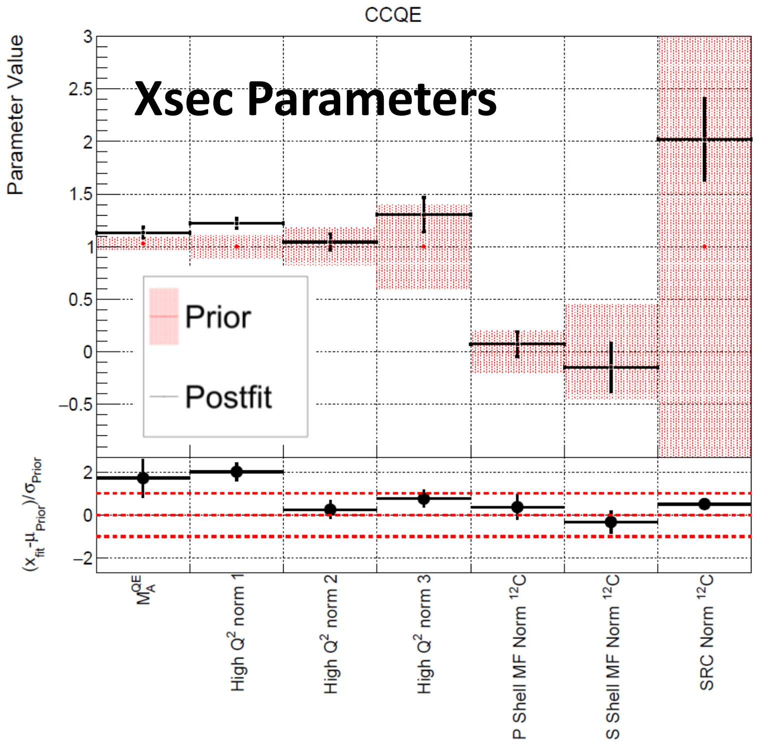
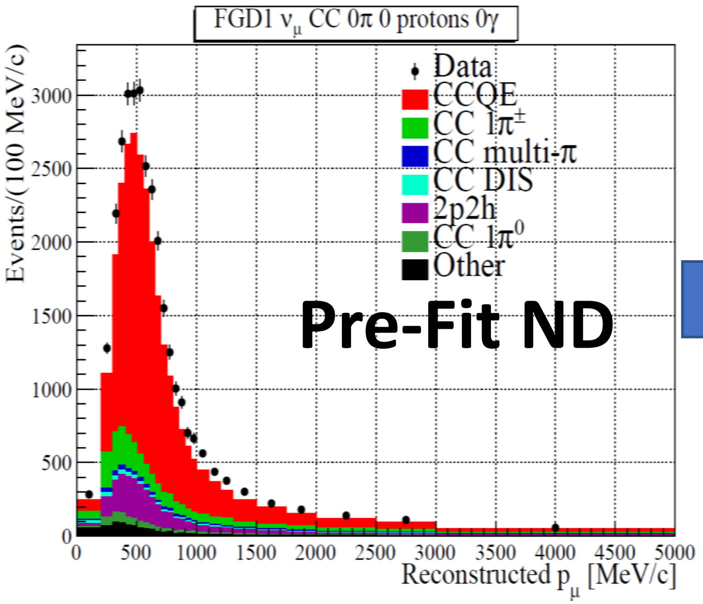
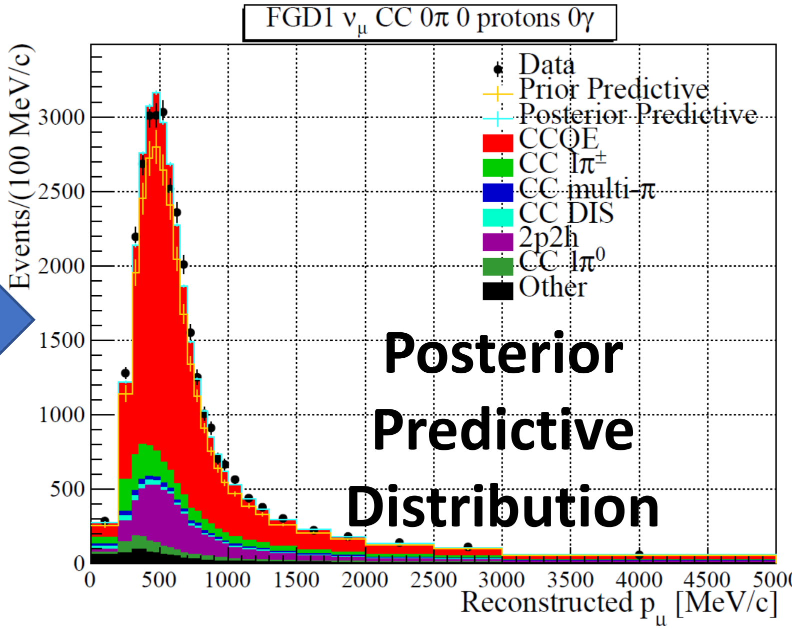
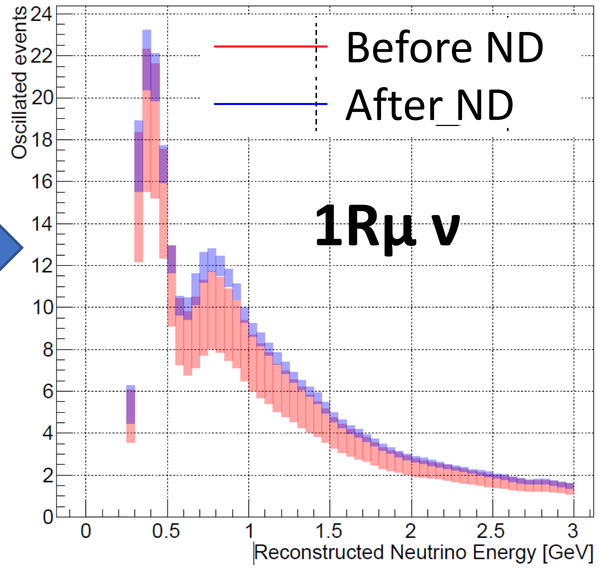




Data Fit



Passing ND constrains



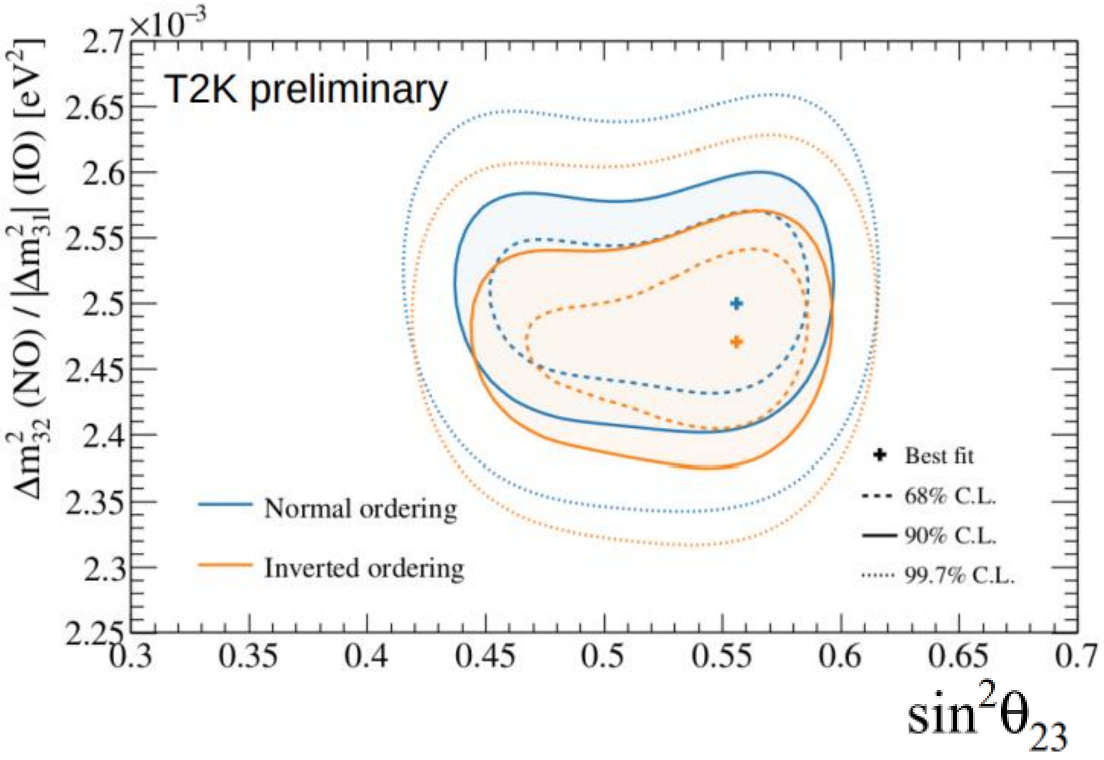
After propagating ND constrained parameters

- Smaller error
- Spectrum shape changes, similar as in ND

Atmospheric parameters

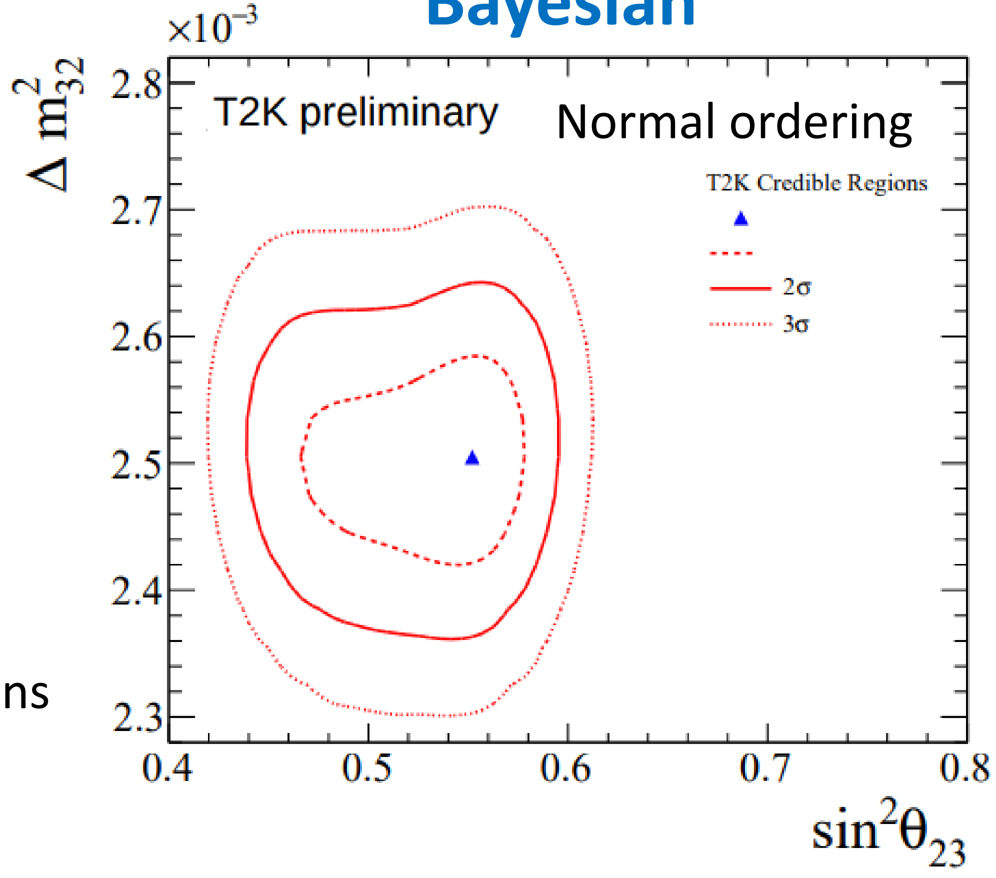
- Best fit point in the upper octant
- Lower octant still allowed at the 68% CL level

Frequentist



Reactor Constrains Applied

Bayesian

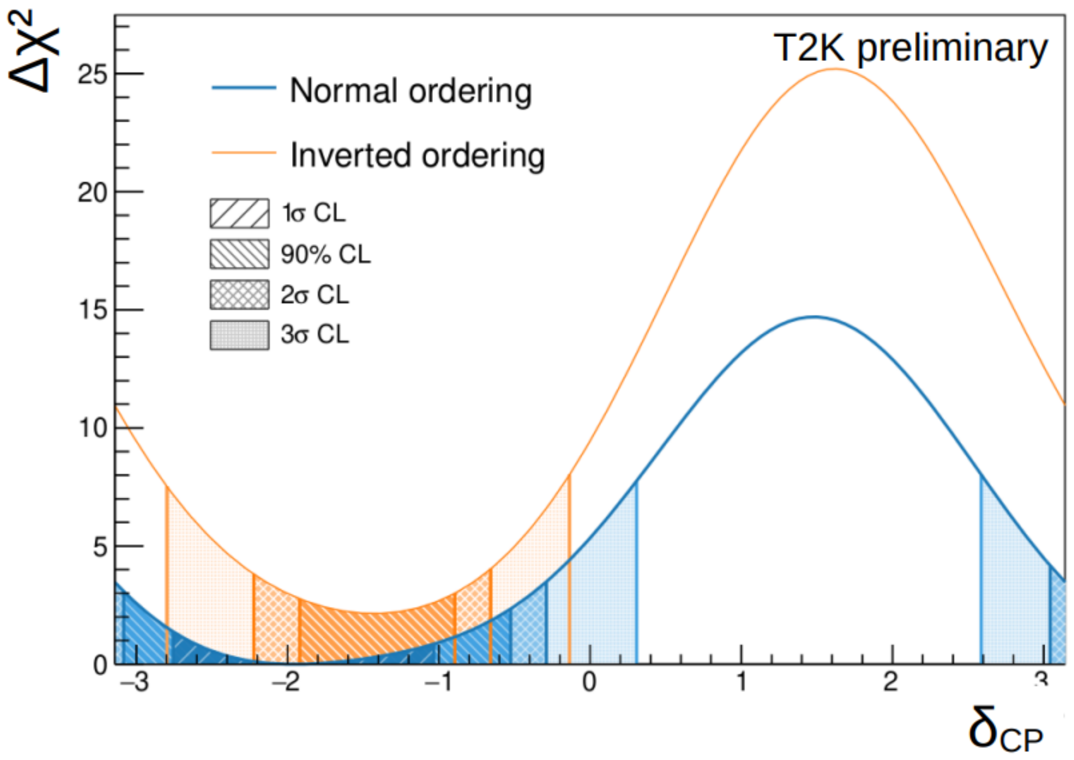


CP phase

- CP-conserving values of δ_{CP}= 0 and δ_{CP} = π both are outside of 90% CL intervals
- Tested effect of alternative interaction model, did not find biases that would change this conclusion

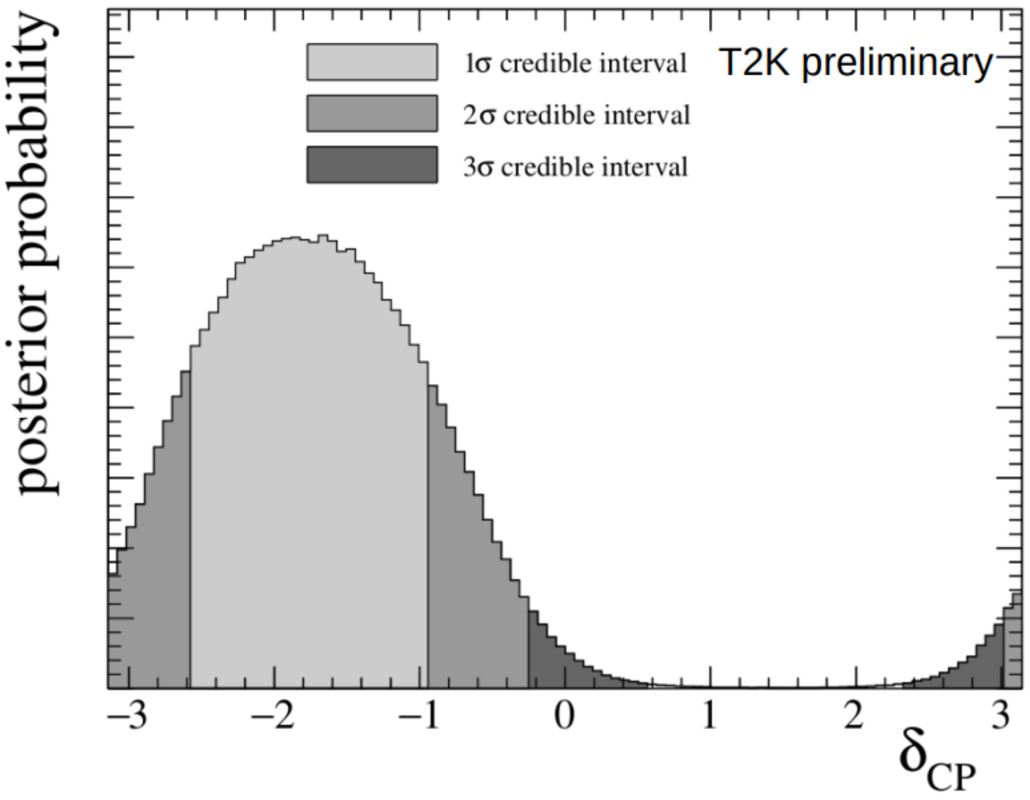
- Performed goodness of fit and obtained Bayesian Posterior Predictive **P-value** of 85%

Frequentist
(Feldman-Cousins method)



Reactor Constrains Applied

Bayesian
(marginalized over MO)



Jarlskog Invariant

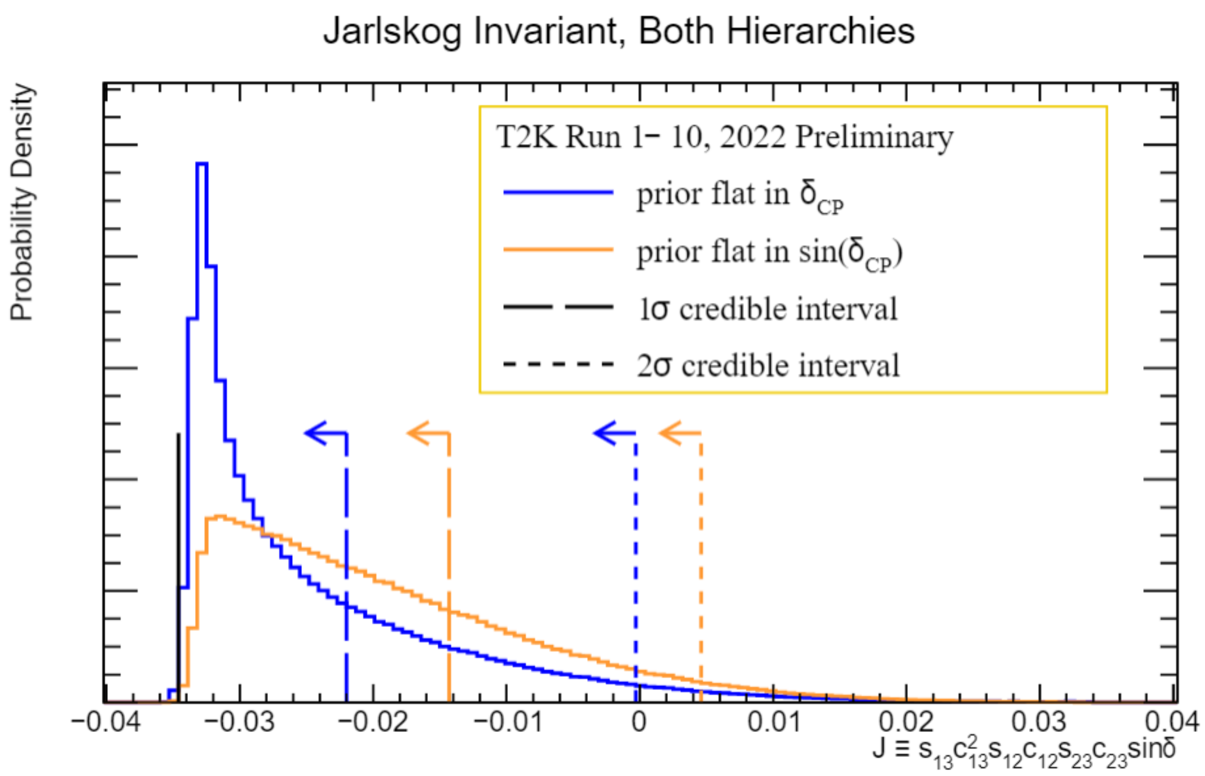
We can perform alternative measurement of CP-violation using Jarlskog invariant.

$$J = s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\sin\delta_{CP}$$

- Search for potential CP violation by looking at the posterior probability and credible intervals for J_{CP}
- Preference for maximal CP-violation independently of prior

Hints of CP violation from measurements of J_{CP}

Bayesian



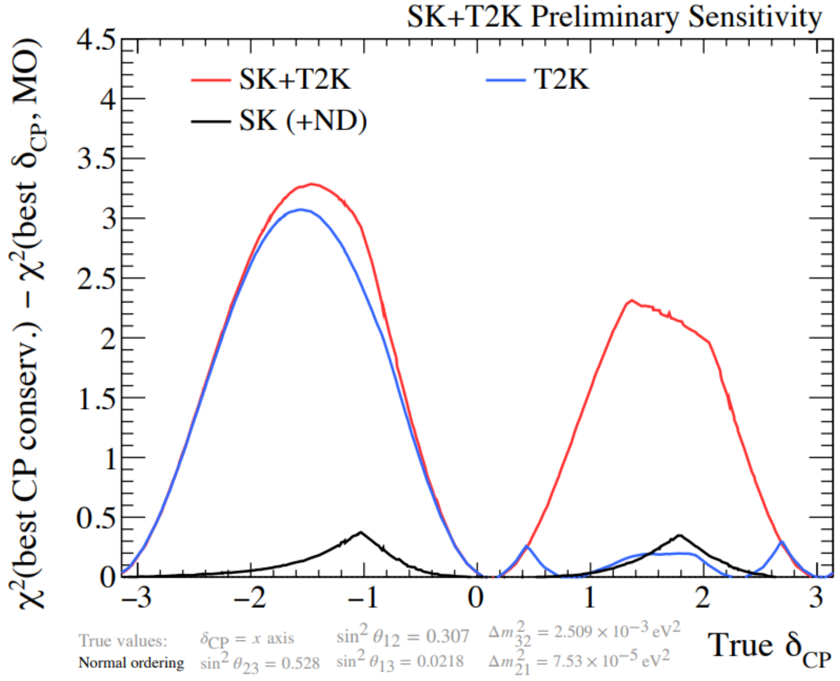
Reactor Constrains Applied


BUT WAIT,
there's more!

Joint Fits

T2K-SK atmospheric joint analysis

- Common detector between two experiments: need to check effect of correlations between systematics
- Super-K atmospheric samples cover wider range of energies and baseline than T2K, with in particular sensitivity to **MO** from high energy neutrinos
- Performed sensitivity studies for the common analysis



T2K-NOvA joint analysis

- 2 long baseline experiments with different baselines, energy ranges and detector technologies: complementarity to study oscillations
- Two collaborations have started work on a joint analysis of their data

Experimental Property	T2K	NOvA
Proton Beam Energy	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection Technology	Water Cherenkov	Segmented liquid sintillator bars
CP Effect*	32%	22%
Matter Effect	9%	29%

*Minimum difference of $\sin(\delta_{cp})=0$ and $\sin(\delta_{cp})=\pm1$, neutrinos and antineutrinos

Summary

Despite World situation T2K is alive and keeps pushing forward.

Conservation of CP symmetry excluded at the 90% CL level
Mild preference for normal ordering and upper octant

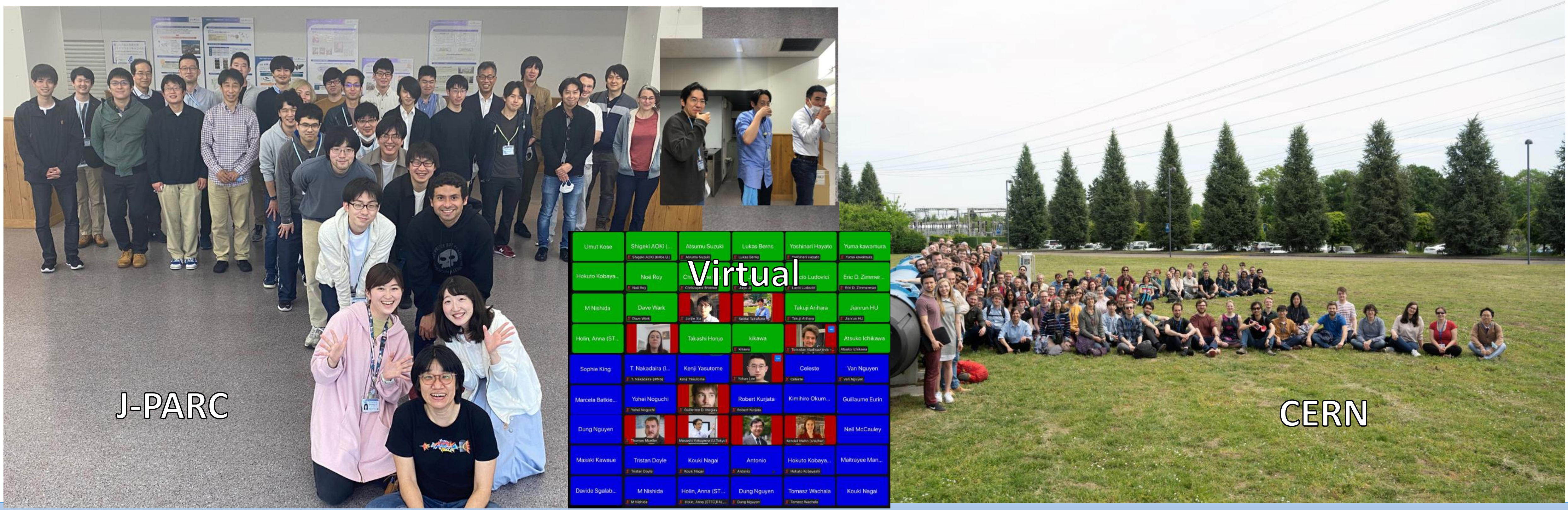
- Use of NA61/SHINE 2010 replica target data for hadron production
- Improved uncertainties for spectral function model and additional uncertainties for resonant and multi-π events, as well as final state interactions
- First use of proton and photon tagging at ND
- First use of multi-ring events in T2K FD
- New analysis with more sophisticated and robust analysis model: stable results with respect to Nature paper.

Joint analyses with NOVA beam ν and Super-Kamiokande atmospheric ν in preparation.

On-going **upgrade** of the accelerator and near detectors, and FD loaded with Gadolinium sulfonate. See next T2K talk

T2K Collaboration

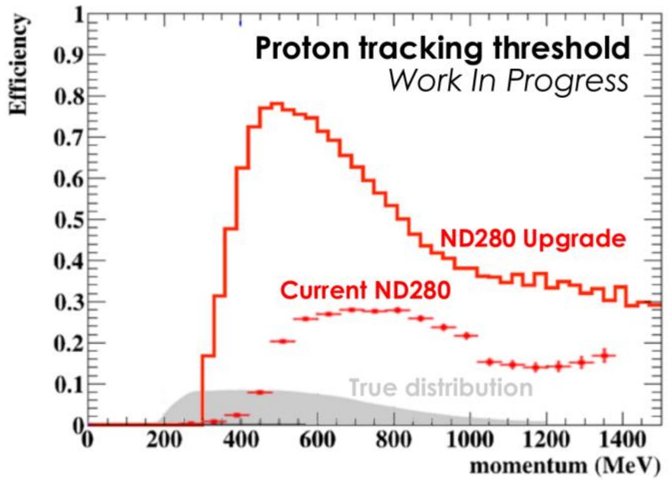
Three flavor collaboration meeting
CERN+J-PARC+Virtual
May 2022

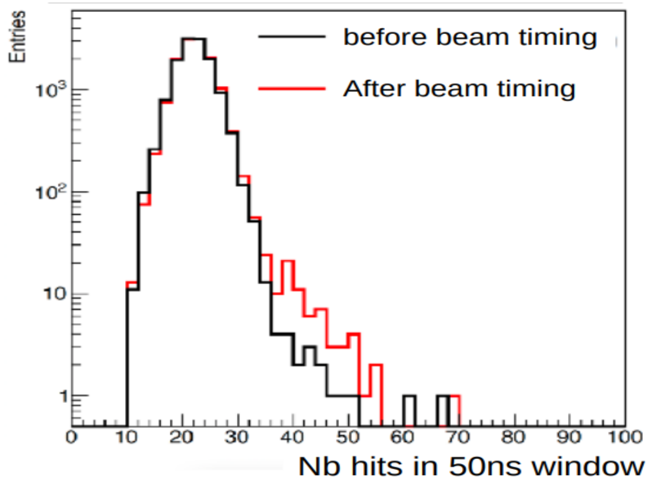


BACKUP

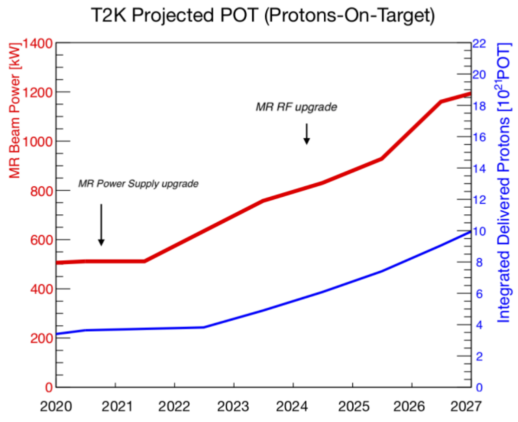
T2K Upgrades

Near detector upgrade
- P0D will be replaced by a complex of new detectors
- Improved ability to study neutrino interactions, both for cross-section measurements and constraining uncertainties in oscillation analysis
- Expect to start data taking in 2023



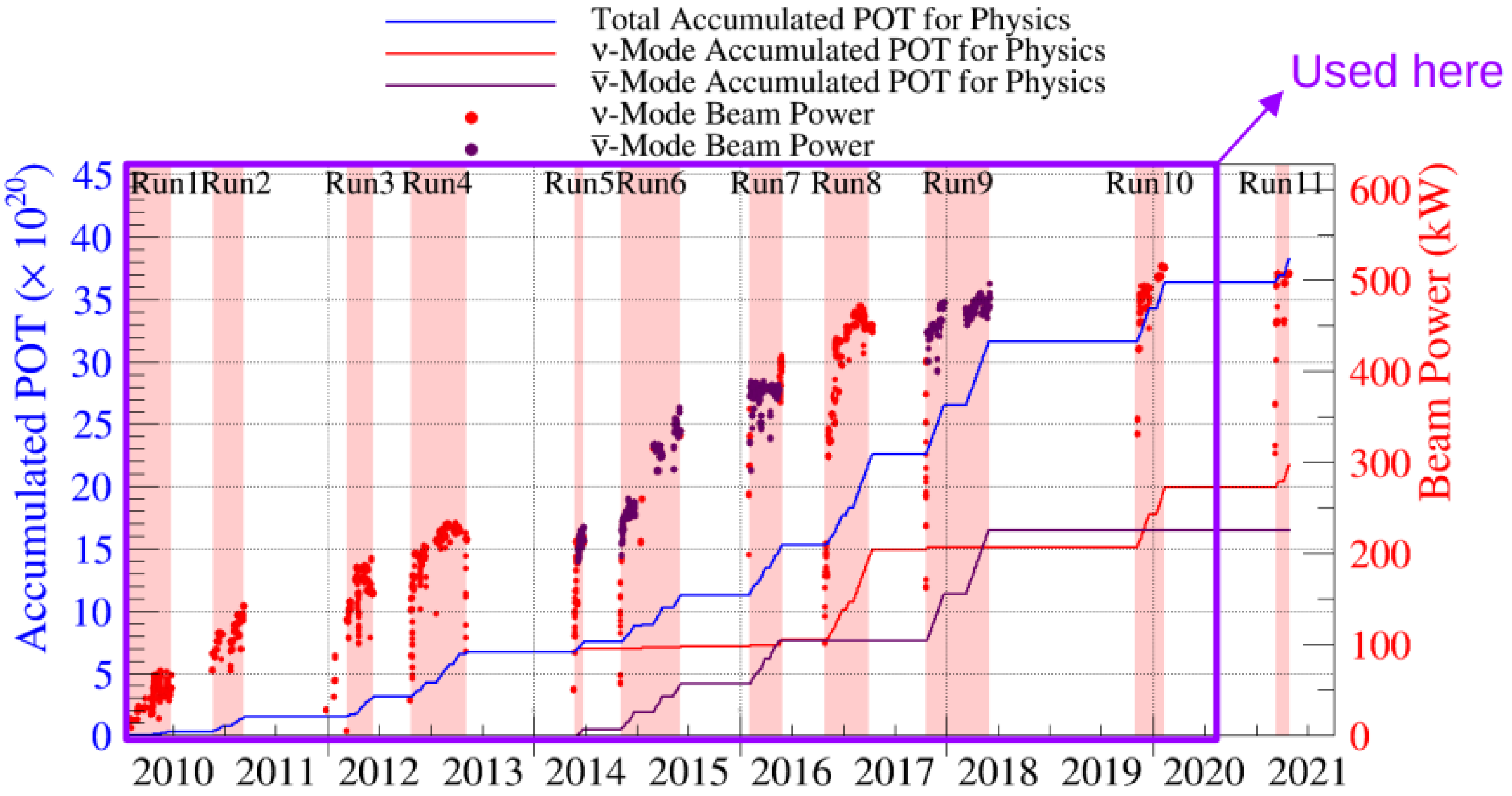


SK-GD
- Super-K was loaded with Gadolinium sulfate, giving improved neutron tagging ability (summer of 2020)
- T2K already recorded data ("Run 11") during this SK-Gd phase, not yet used in analysis
- Second phase of Gd loading started in May



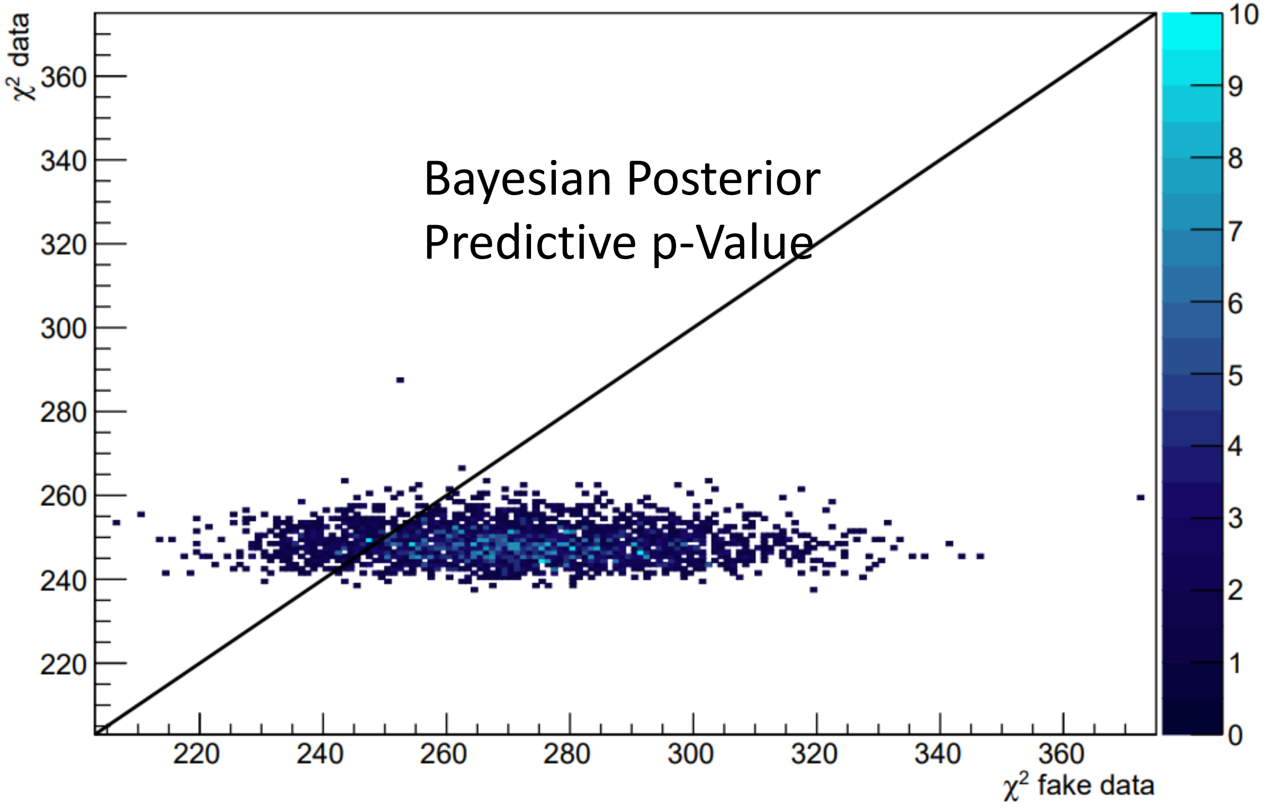
J-PARC accelerator upgrade
- Will allow operation at higher beam intensity
- Upgrade of the neutrino beamline in parallel to handle higher intensity beam
- Upgrade of horn power supplies for better focusing
- Expected to be ready for operation in early 2023

Accumulated POT



P-Value

- Obtained Bayesian posterior predictive p-value is equal to 86%



Systematic uncertainties FD

Error source (units: %)	1R FHC	1R RHC	MR FHC $CC1\pi^+$	1Re FHC	1Re RHC	1Re FHC $CC1\pi^+$	1Re FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6	1.2
Total All	3.4	3.9	4.9	5.2	5.8	14.3	4.5

Note:

● Numbers quoted are the RMS of the predicted numbers of events in the far detector sample obtained when varying systematic parameters according to their prior distribution

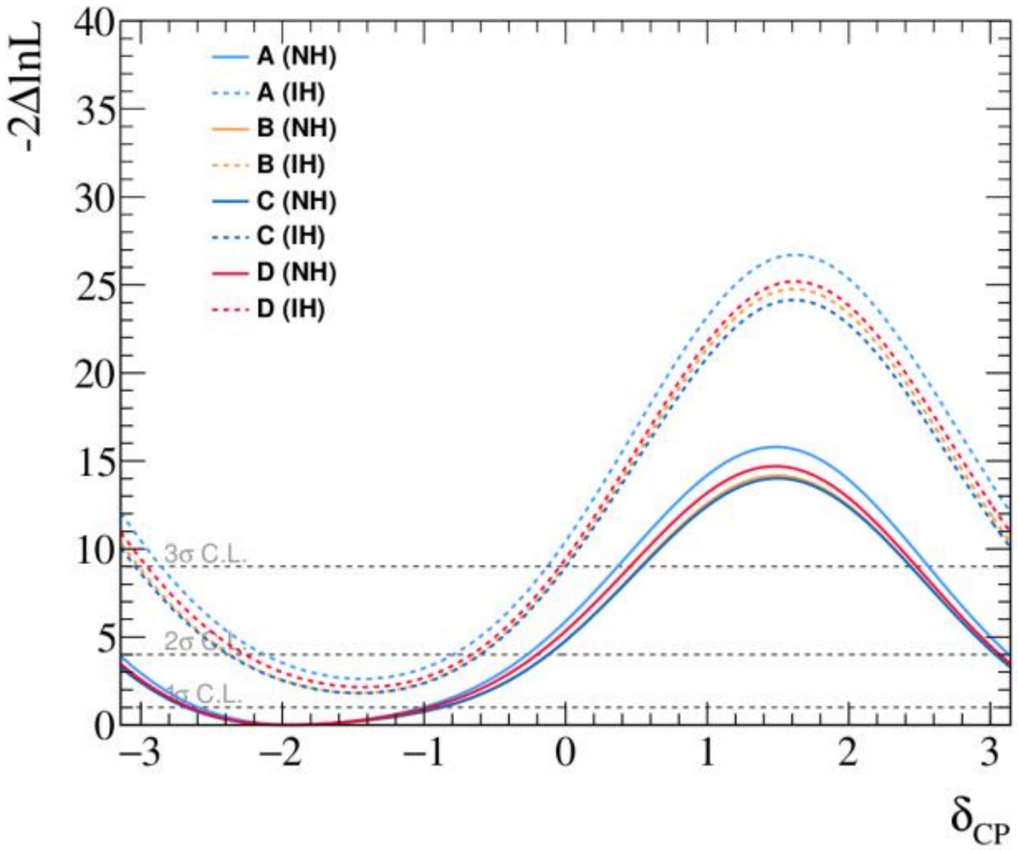
● Some systematic parameters do not have a prior constraint, and can end up having larger effect than estimated with this method in a fit

Systematic uncertainties ND

Sample	$\delta N/N(\%)$							
	Flux		Xsec		ND280		Total	
	pri.	post.	pri.	post.	pri.	post.	pri.	post.
FGD1 FHC CC0π-0p-0γ	5.0	2.7	11.8	2.8	1.8	1.2	12.8	0.6
FGD1 FHC CC0π-Np-0γ	5.5	2.8	11.7	3.2	3.5	2.2	12.9	0.9
FGD1 FHC CC1π-0γ	5.2	2.7	9.1	2.7	3.0	1.4	10.6	1.0
FGD1 FHC CC-Other-0γ	5.4	2.8	8.0	2.8	5.2	2.3	11.0	1.6
FGD1 FHC CC-Photon	5.5	2.8	8.5	2.8	2.8	1.8	10.5	0.8
FGD2 FHC CC0π-0p-0γ	5.1	2.7	11.2	2.8	2.1	1.1	11.5	0.6
FGD2 FHC CC0π-Np-0γ	5.5	2.8	11.3	3.3	3.9	2.4	12.2	1.0
FGD2 FHC CC1π-0γ	5.2	2.7	9.0	2.7	3.6	1.6	10.5	1.0
FGD2 FHC CC-Other-0γ	5.6	2.8	8.0	2.8	6.3	2.7	11.5	1.9
FGD2 FHC CC-Photon	5.4	2.8	8.3	2.8	2.5	1.6	10.4	0.8
FGD1 RHC CC0π	4.9	3.2	11.3	3.2	1.9	1.2	12.2	0.9
FGD1 RHC CC1π	4.6	3.1	10.3	3.0	4.2	2.6	11.4	1.9
FGD1 RHC CC-Other	4.5	2.9	9.3	3.0	3.5	2.0	10.5	1.5
FGD2 RHC CC0π	4.8	3.2	10.4	3.0	2.1	1.2	13.8	0.9
FGD2 RHC CC1π	4.6	3.0	9.9	3.2	3.9	2.3	10.9	1.9
FGD2 RHC CC-Other	4.6	2.9	9.7	3.1	2.9	1.8	11.3	1.4
FGD1 RHC BKG CC0π	5.8	2.8	10.1	2.8	2.2	1.1	10.6	1.1
FGD1 RHC BKG CC1π	5.6	2.8	8.0	2.5	3.3	1.6	11.2	1.3
FGD1 RHC BKG CC-Other	5.9	2.9	8.6	2.7	2.6	1.4	10.1	1.4
FGD2 RHC BKG CC0π	5.8	2.8	9.5	2.8	2.2	1.1	10.4	1.1
FGD2 RHC BKG CC1π	5.6	2.8	8.2	2.5	3.2	1.6	10.7	1.3
FGD2 RHC BKG CC-Other	5.9	2.9	8.6	2.7	2.5	1.4	10.6	1.4
Total	4.5	2.7	8.0	2.6	2.1	1.2	9.1	0.3

Effect of Analysis Change

A: Neutrino 2020 result
B: New interaction model and near detector fit
C: B + new θ_{13} reactor constraint (PDG 2019 → PDG2021)
D: C + new sample (ν_μ CC1π^+)



Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

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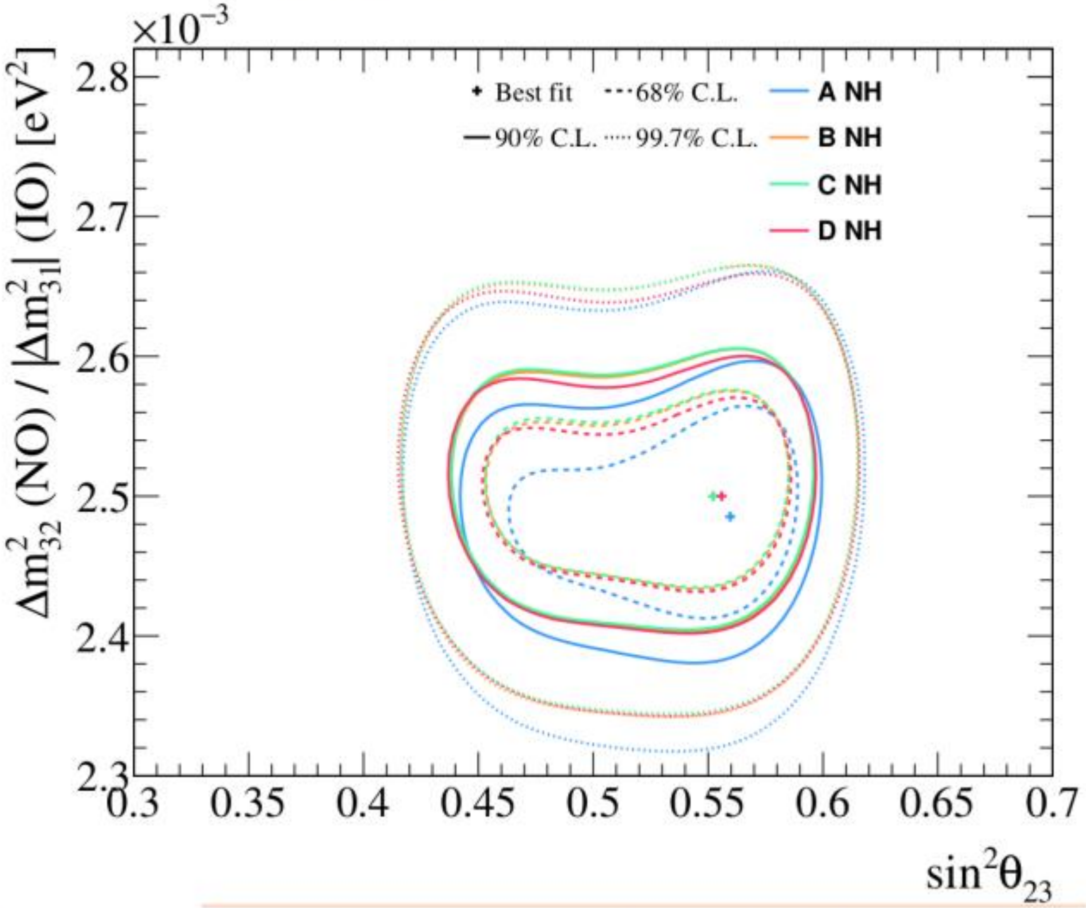

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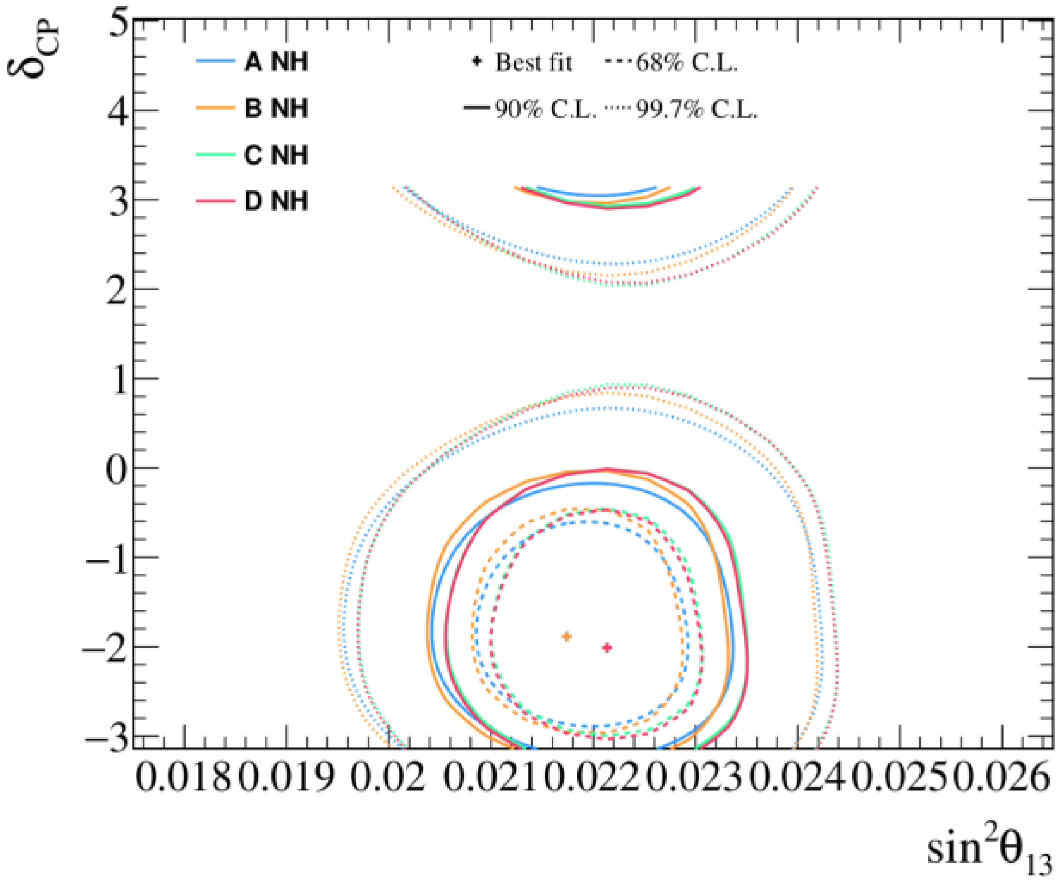

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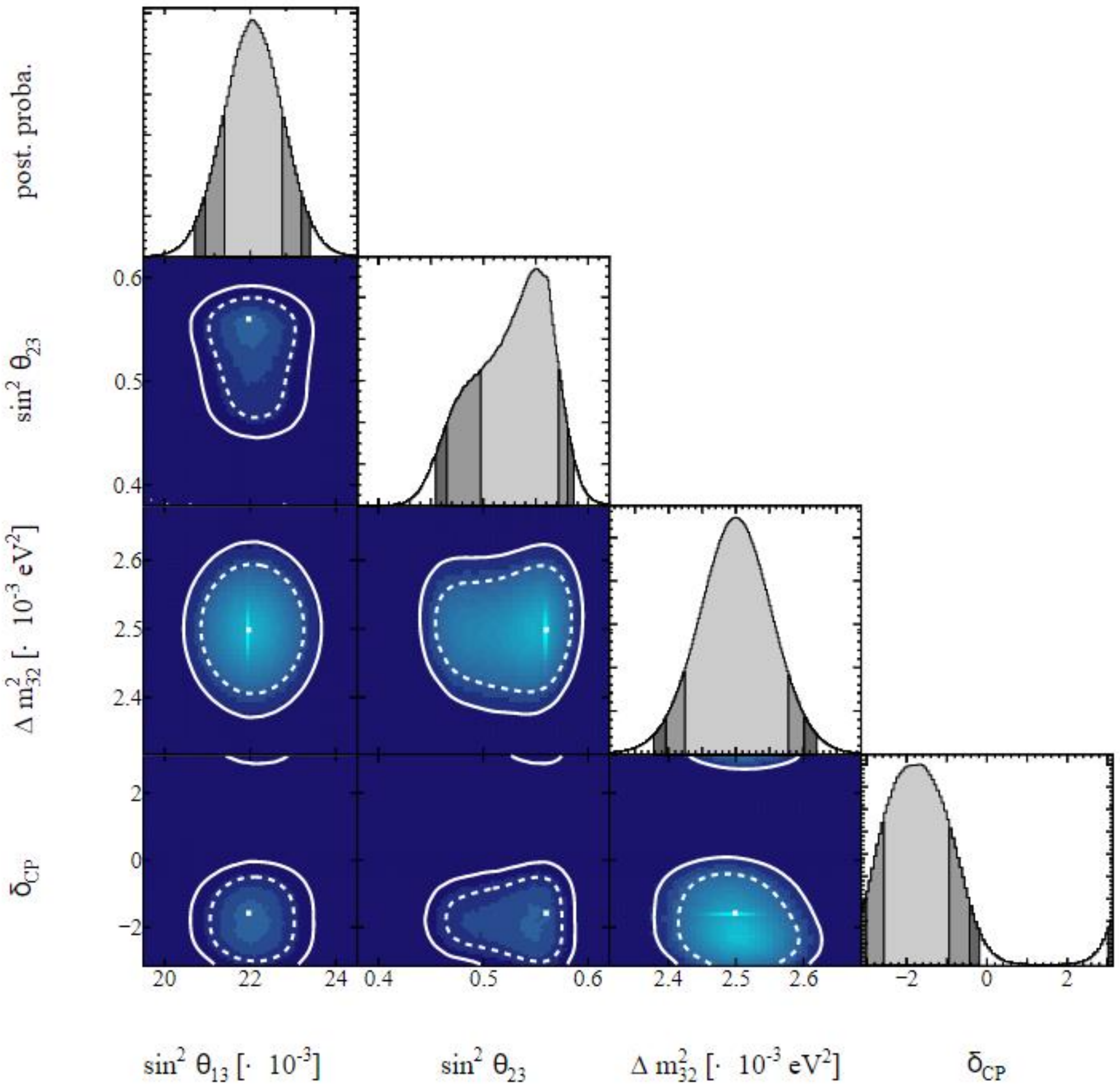
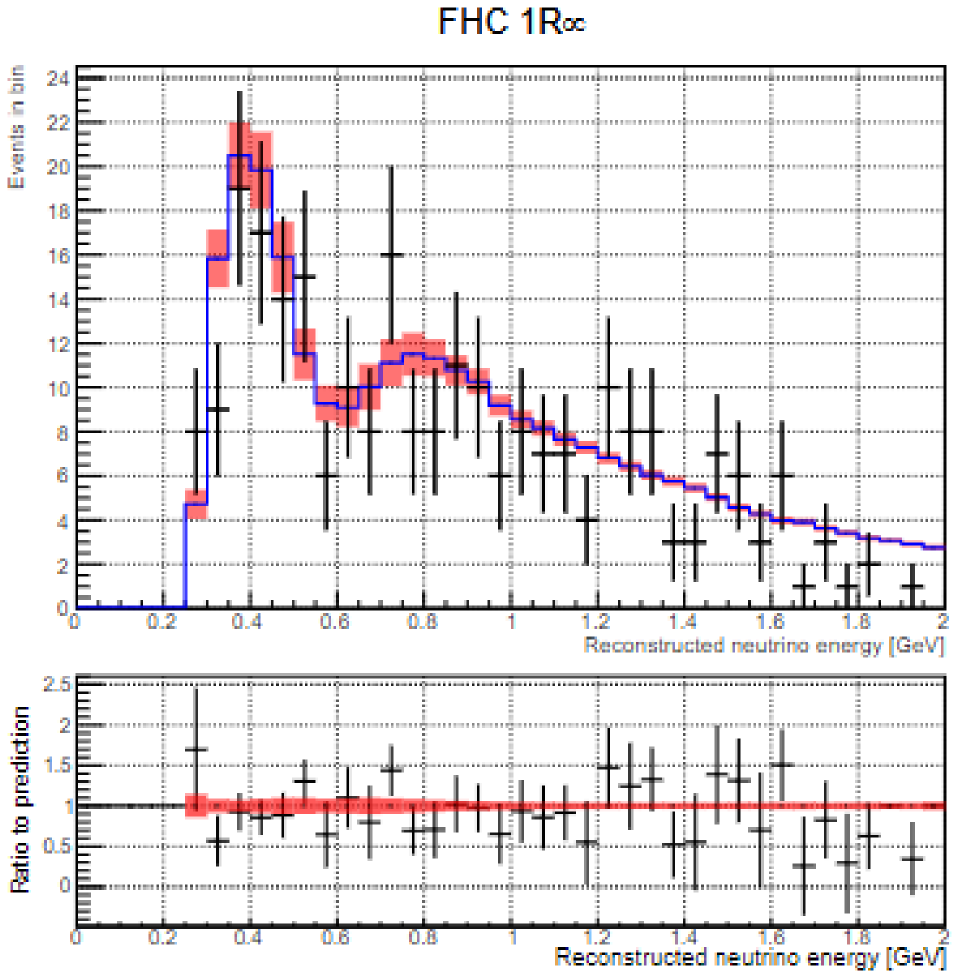
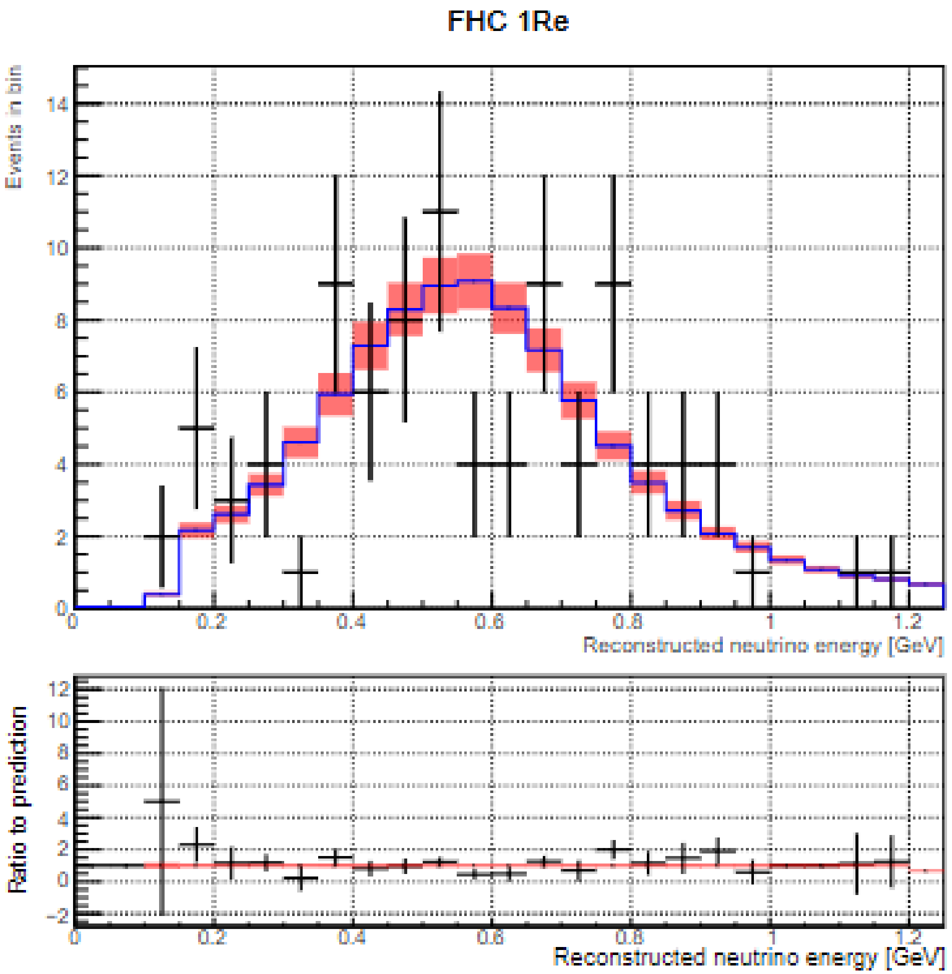
Triangle Plot



Posterior Predicive





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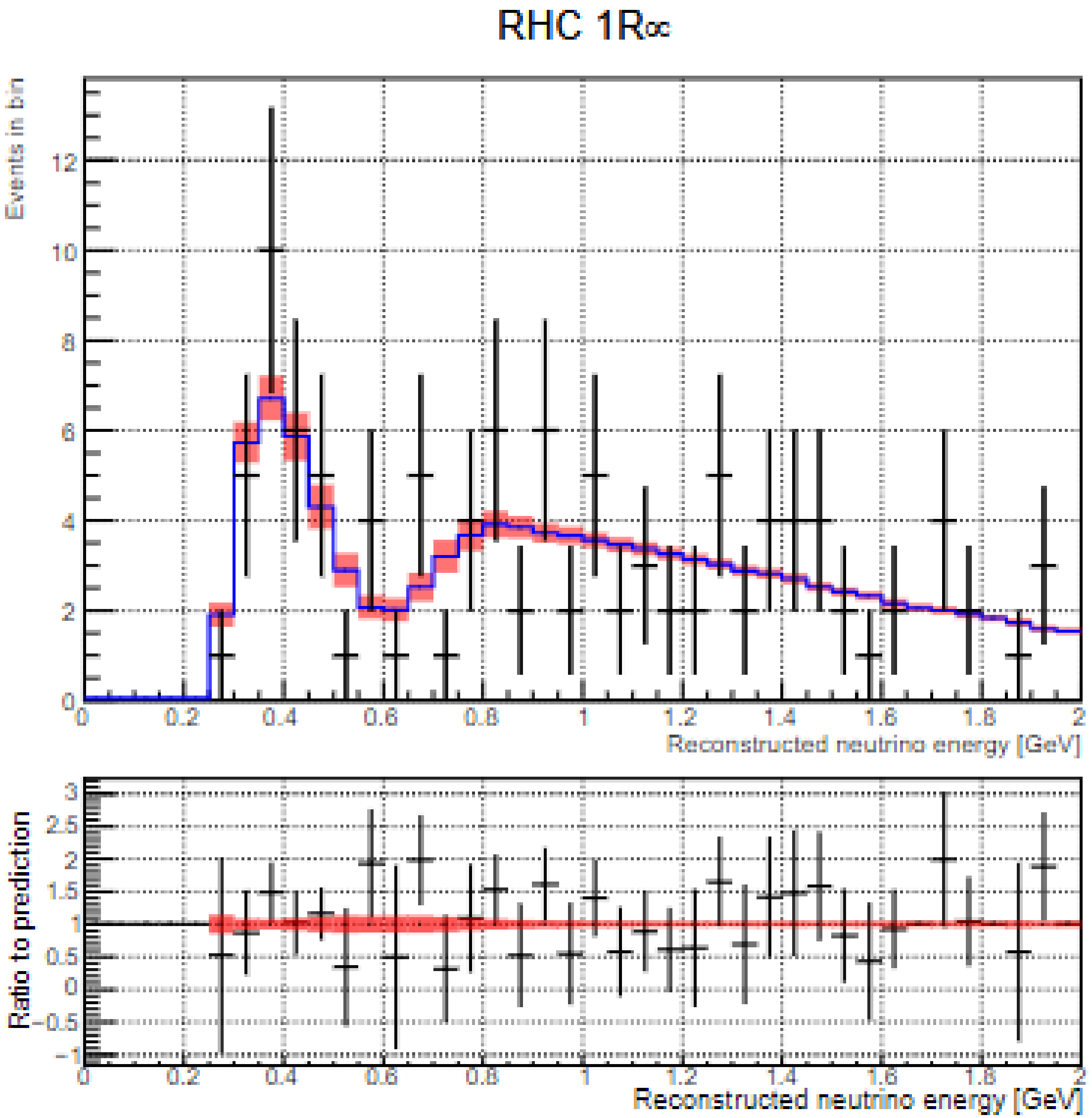

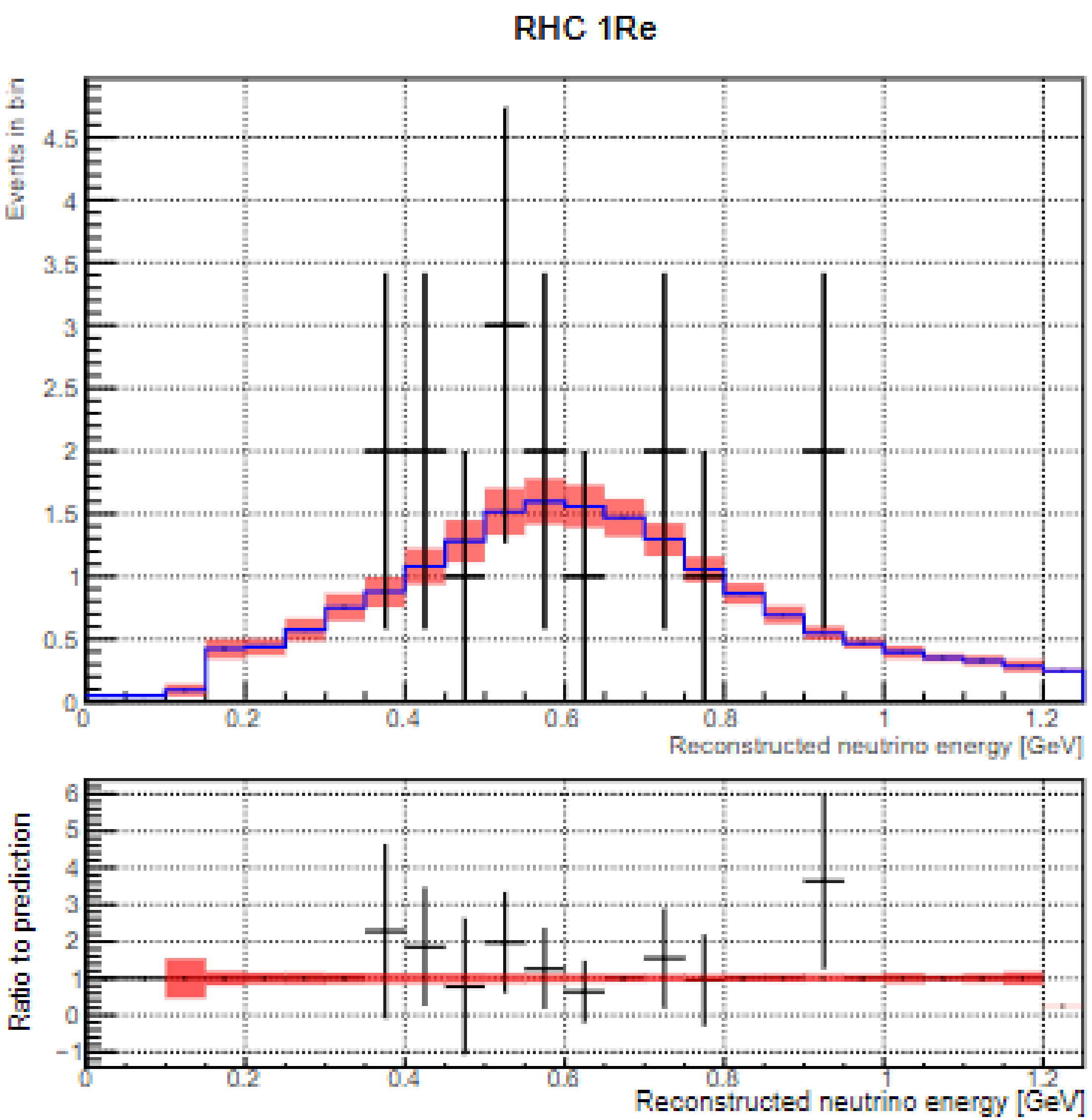

Posterior Predicive