New T2K Oscillation Results

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Introduction

Oscillation analysis is the main T2K result and is performed by several people.

I was the main analyser at theT2K near detector.

Lakshmi Mohan (NCBJ post-doc) contributed greatly to Super-Kamiokande analysis.

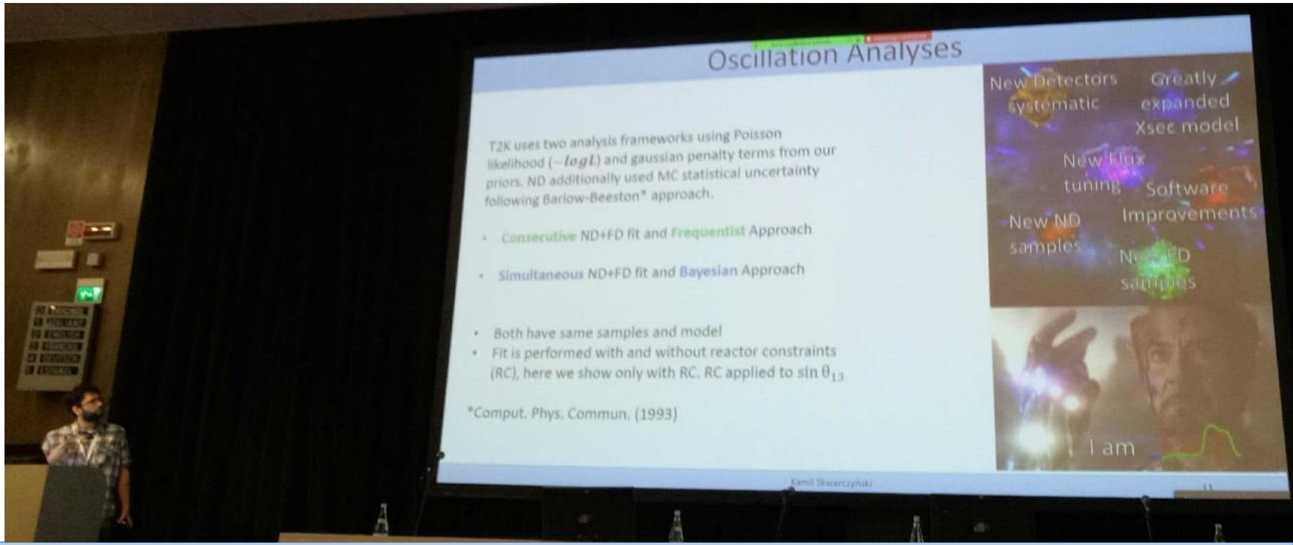
This is the first time any Polish group contributed so greatly to the analysis.

I had the honour to present those results at the ICHEP conference.

This talk is both summary of the T2K main results and my thesis although the thesis contains much more studies ;)

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

ICHEP 2022 Conference

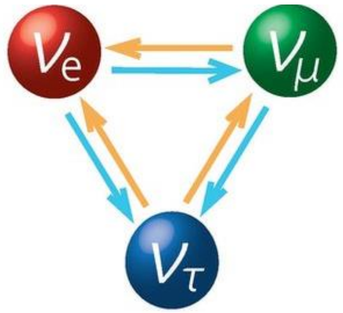


Supervisor: Justyna Łagoda

Outline

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

CP violation in lepton sector



Neutrinos while travelling can change the flavour, this phenomenon is called neutrino oscillations.

The crucial objective of current neutrino experiments is to study if there is CP violation in the lepton sector or not.

Appearance channel

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

CP violation in lepton sector means that neutrino oscillation probabilities are different than for antineutrino.

Parameter describing CP violation is $\boldsymbol{\delta_{CP}}$.

Neutrino CP violation can be three magnitudes larger than in the quark sector.

Studying this effect has potential to answer the question of why there is more matter than antimatter in the Universe.

Jarlskog Invariant in general

$$J = \frac{1}{8}\,\mathrm{Im}\left[U_{23}U_{12}U^*_{22}U^*_{13}\right]$$

Jarlskog Invariant In lepton sector

$$J_{CP,l} = 0.033\sin(\delta_{CP})$$

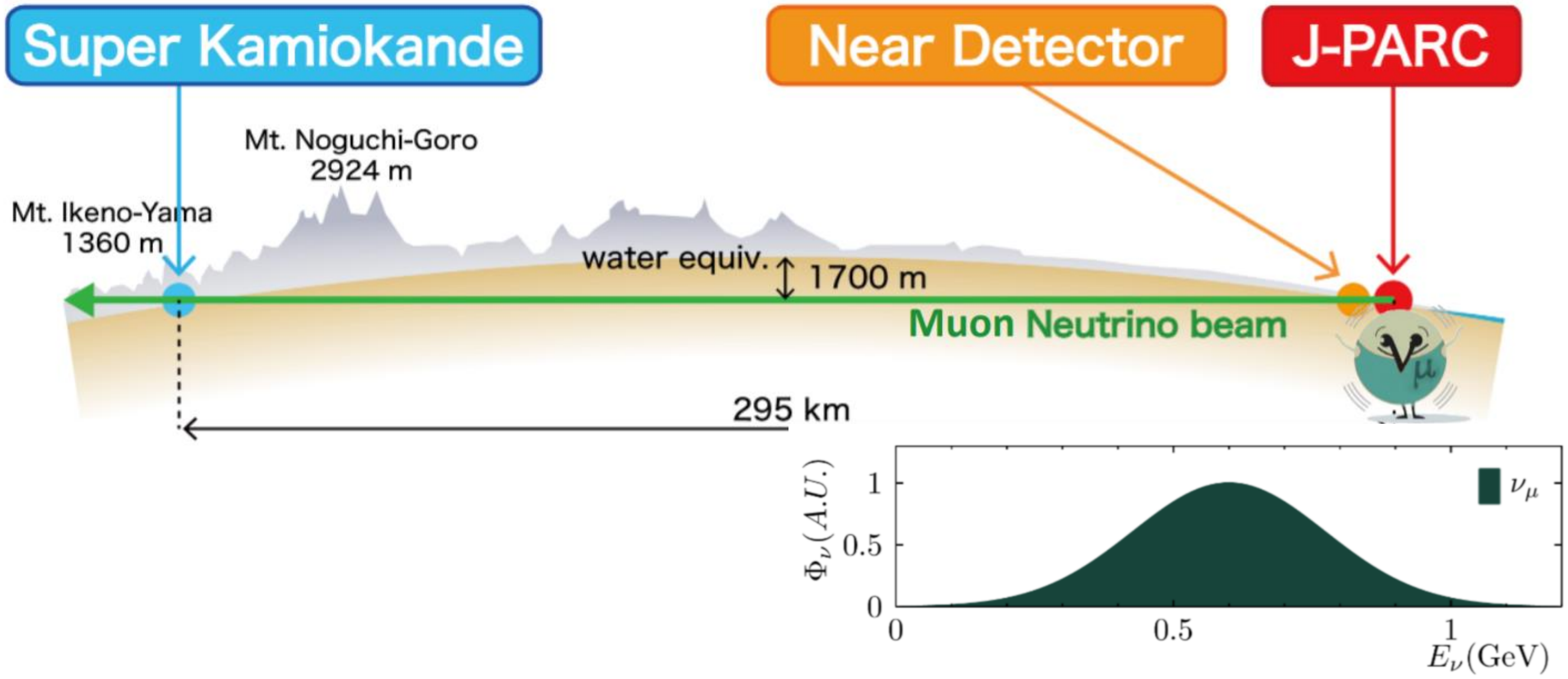
Jarlskog Invariant In quark sector

$$J_{CP,q} = 3 \times 10^{-5}$$

Tokai to Kamioka (T2K) experiment

T2K is located in Japan

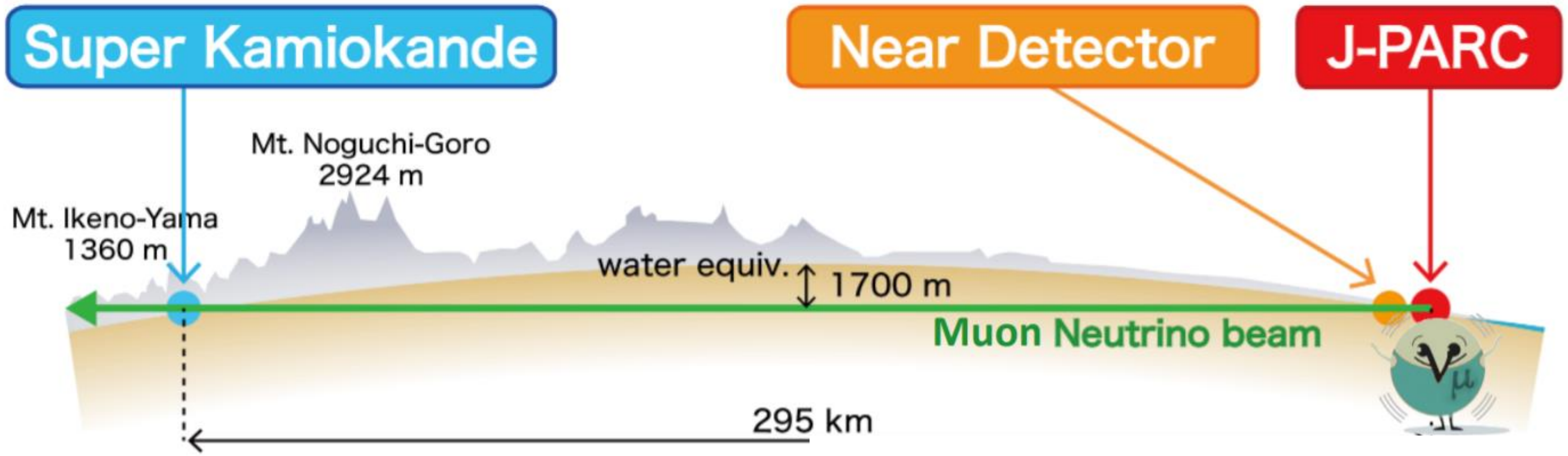
- We create mostly muon neutrinos at J-PARC.

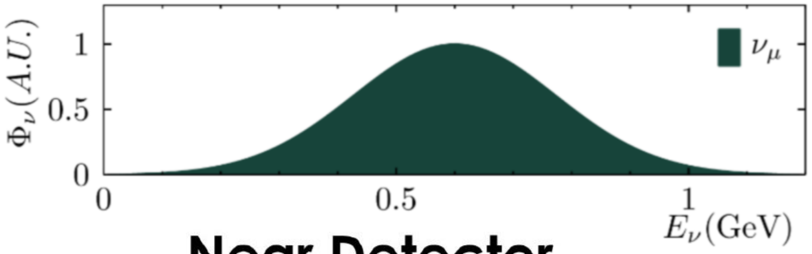


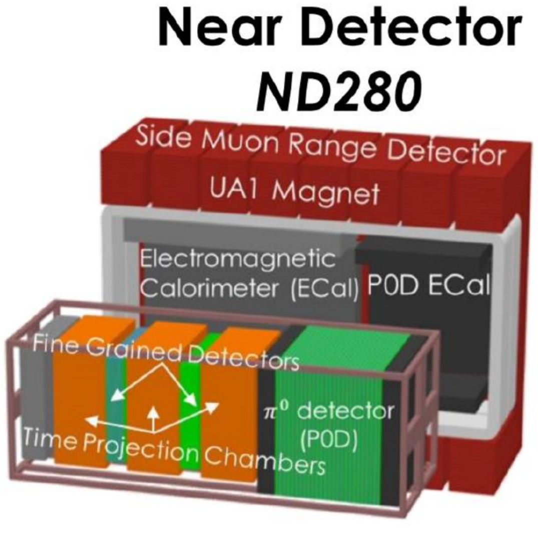
T2K experiment

T2K is located in Japan

- We create mostly muon neutrinos at J-PARC.
- We measure neutrinos with Near Detector.



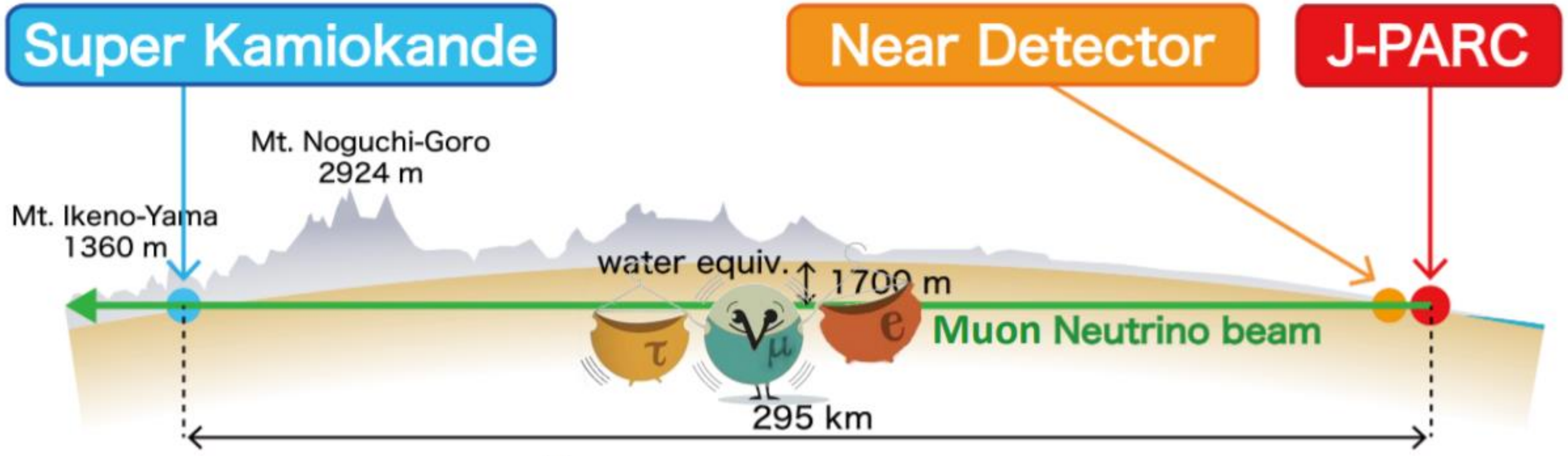


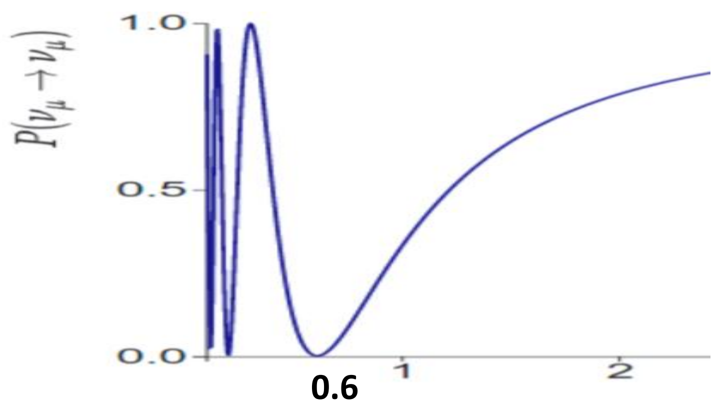


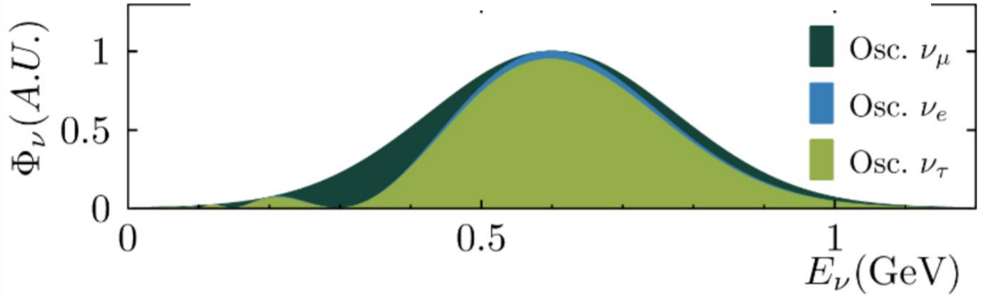
T2K experiment

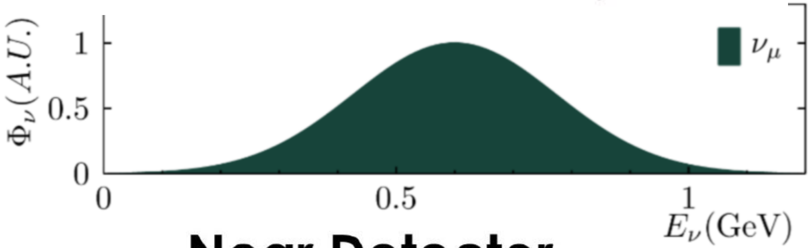
T2K is located in Japan

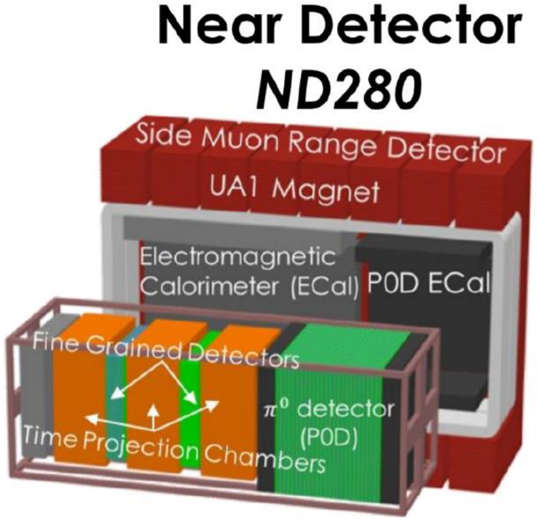
- We create mostly muon neutrinos at J-PARC.
- We measure neutrinos with Near Detector.
- Neutrinos oscillate.







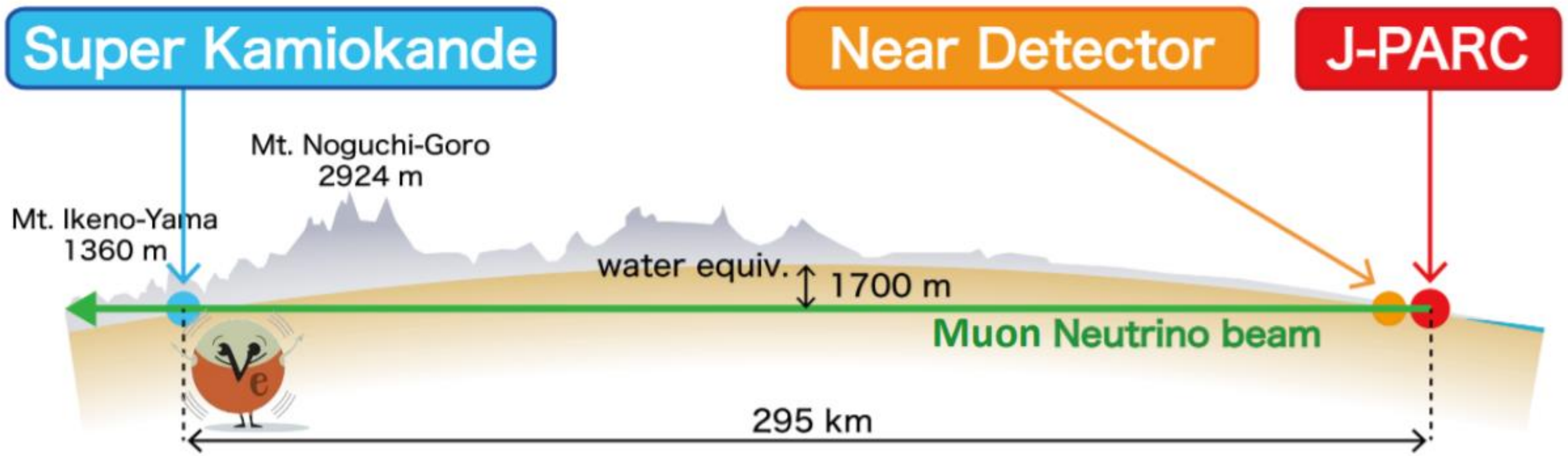




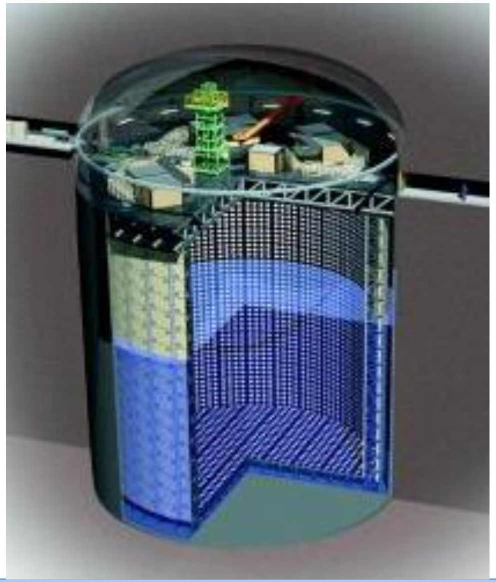
T2K experiment

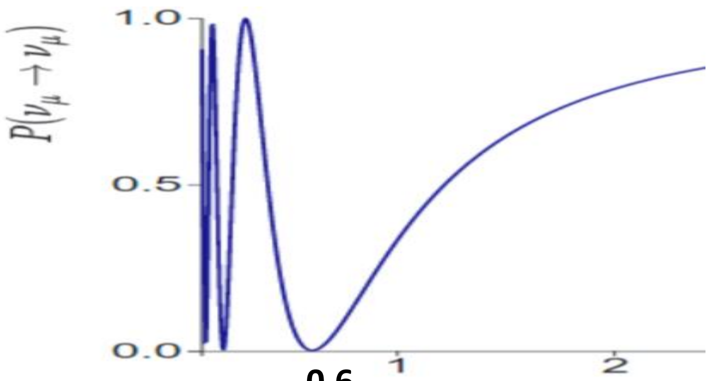
T2K is located in Japan

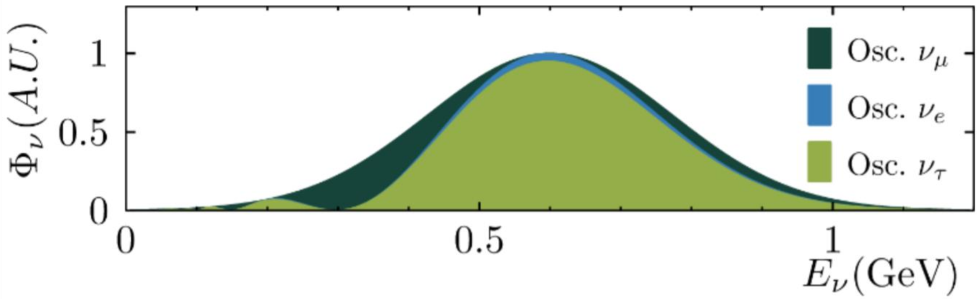
- We create mostly muon neutrinos at J-PARC.
- We measure neutrinos with Near Detector.
- Neutrinos oscillate.
- Neutrinos are measured in Far Detector

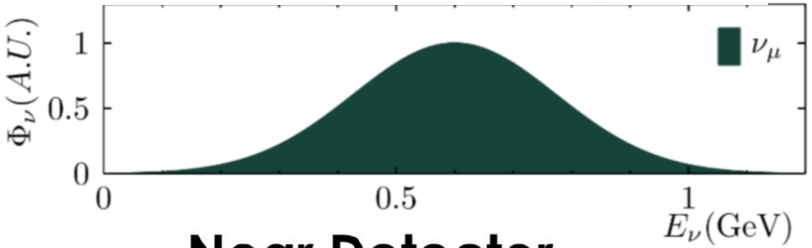


Far Detector
Super Kamiokande

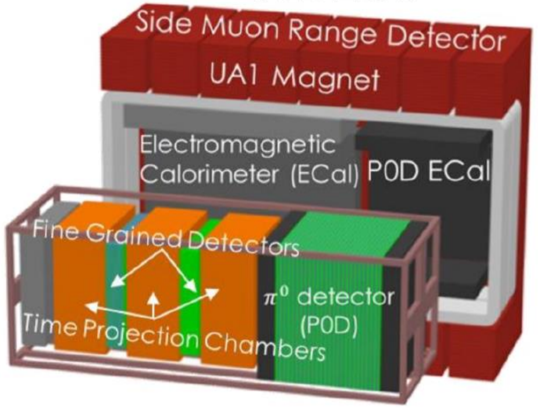








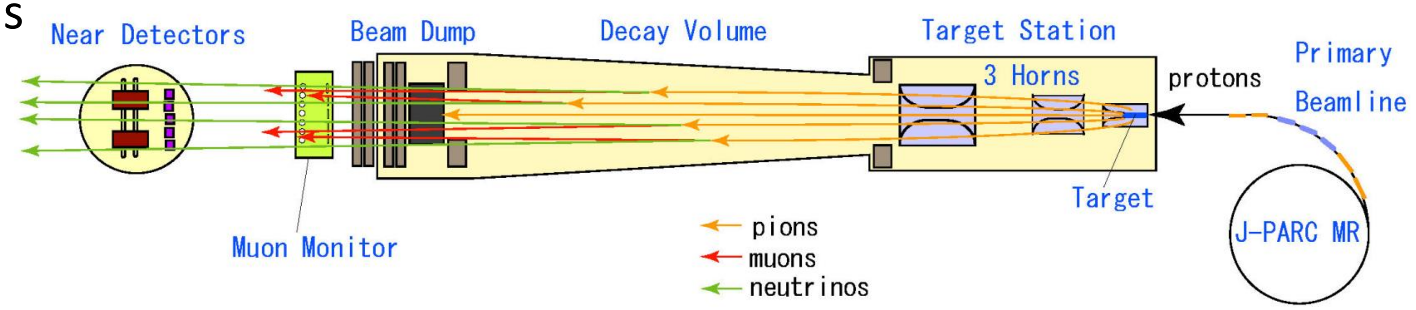
Near Detector
ND280



T2K Beam Production and Flux Predictions

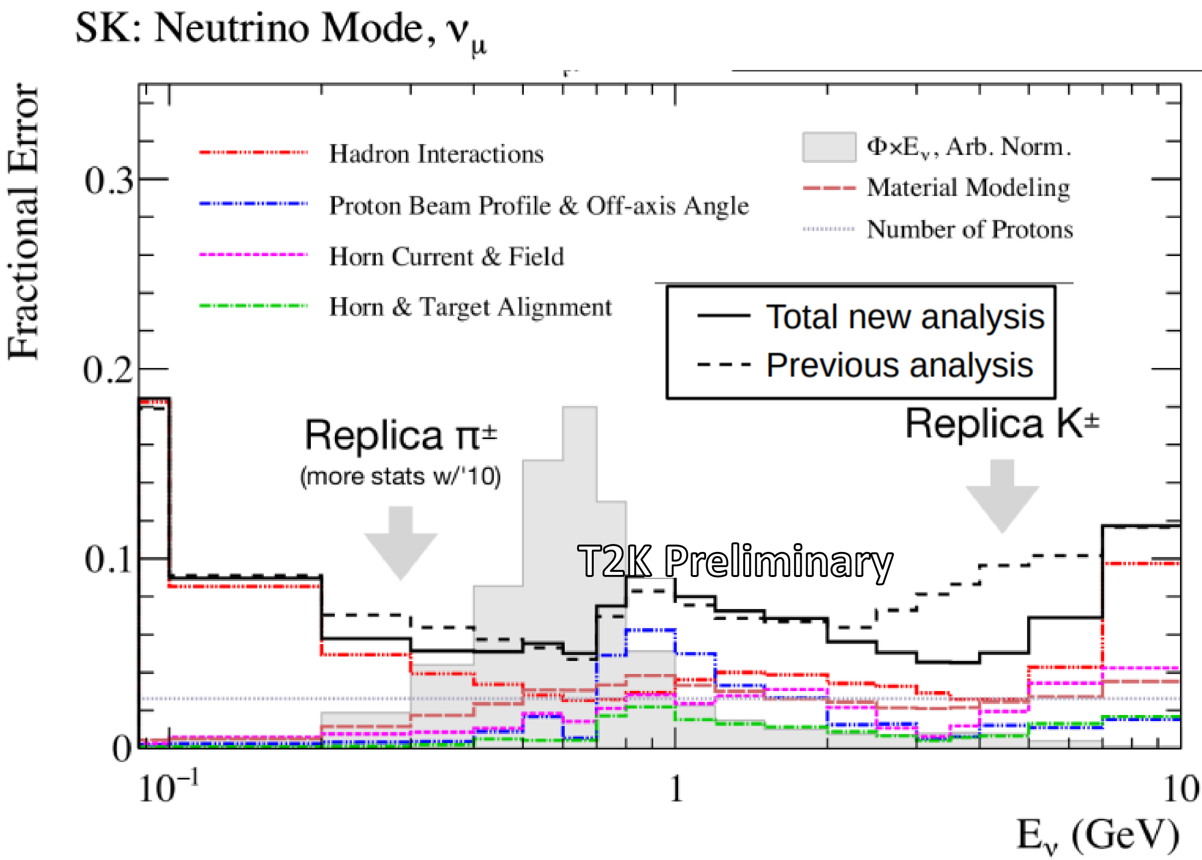
- Protons hit graphite target and produce hadrons (π, K) which are focused and then decay into neutrinos
- Can select $\nu/\bar{\nu}$ beam mode based on horn polarity

Forward Horn Current (**FHC**) - ν mode
Reverse Horn Current (**RHC**) - $\bar{\nu}$ mode



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



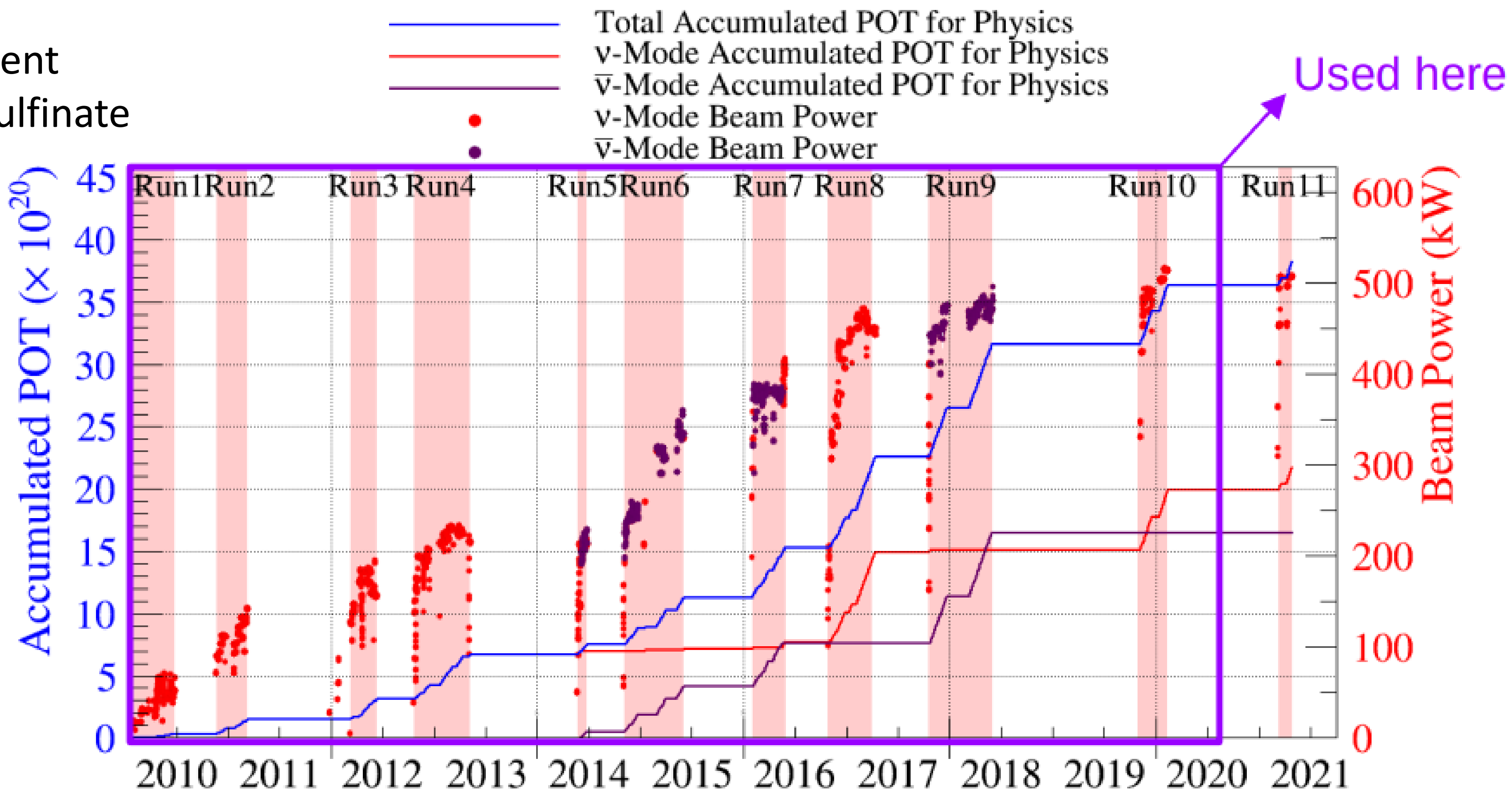
* Eur. Phys. J. C76, 617 (2016)
**Eur. Phys. J. C79, 100 (2019)

Accumulated Data

The analysis presented here includes almost all of the accumulated data by T2K.

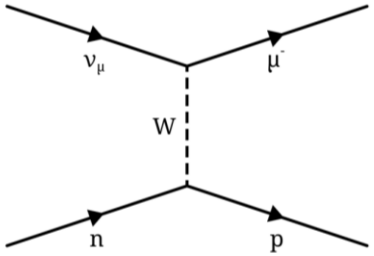
Run 11 is not used as FD underwent significant change. Gadolinium sulfinate was added to the pure water.

POT-Protons on Target

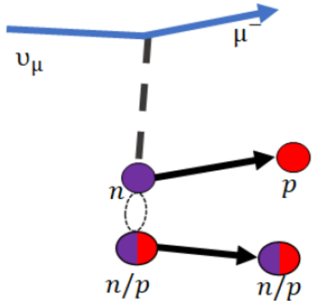


T2K Cross-Section model

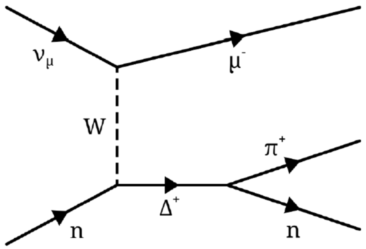
Charge Current Quasi Elastic (**CCQE**)



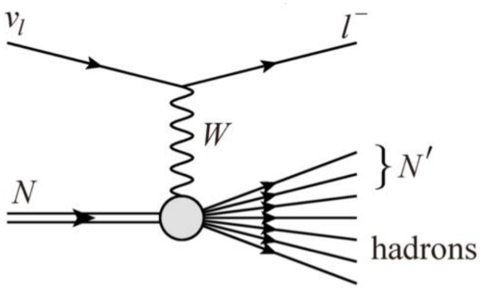
Two Particles Two Holes (2p2h or MEC)



Resonant Scattering (**RES**)

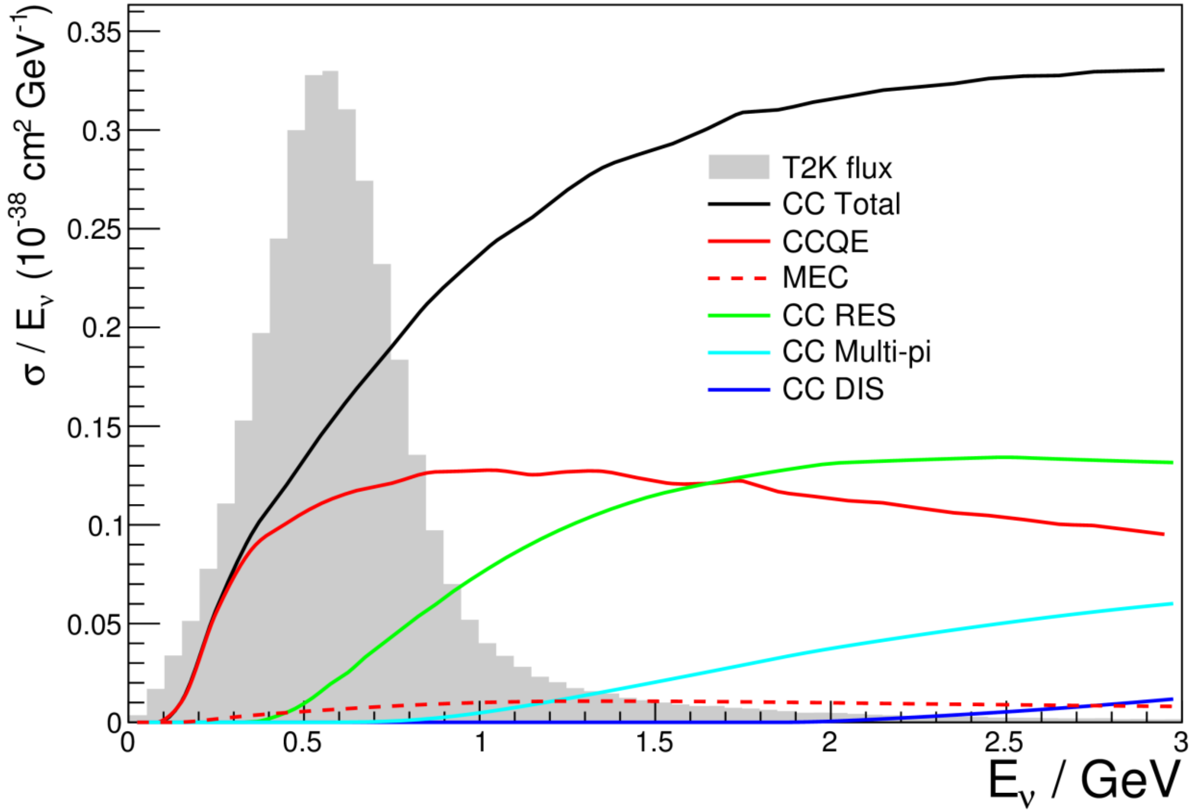


Deep Inelastic Scattering **(DIS)**
and Multi-pi production



T2K cross-section model includes several reactions, dominant of which is **CCQE**

In this analysis there was significant model development and overall number of parameters almost doubled.

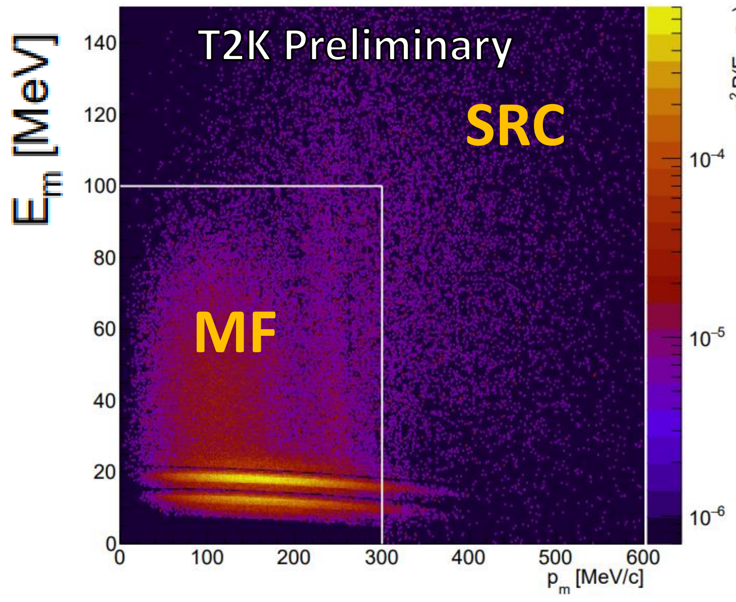


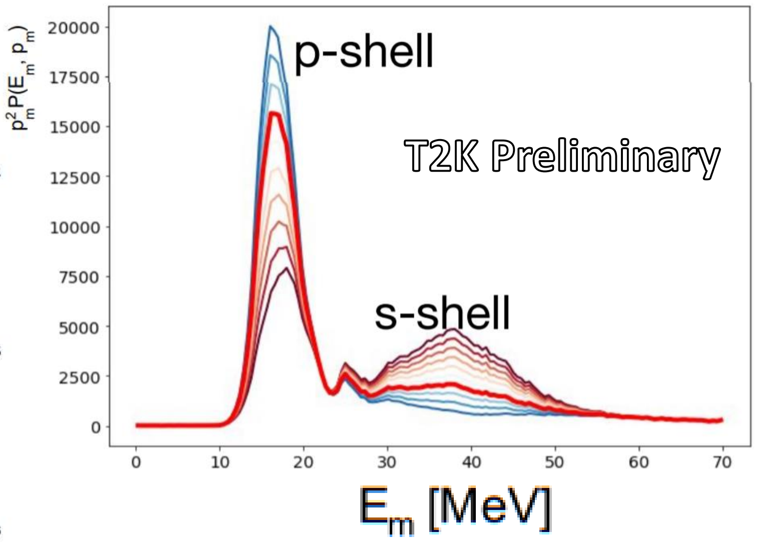
Charge Current Quasi Elastic (**CCQE**)

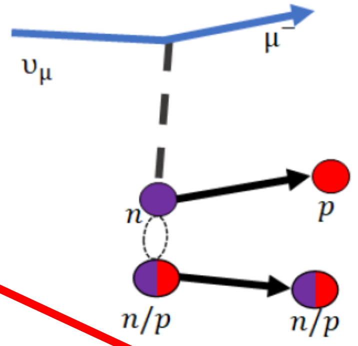
- Expanded parameterization of the spectral function
- Normalization of each nuclear shell for Mean Field (**MF**)
- Normalization of Short Range Correlations (**SRC**)
- Added Pauli Blocking to give more freedom in low Q^2 region

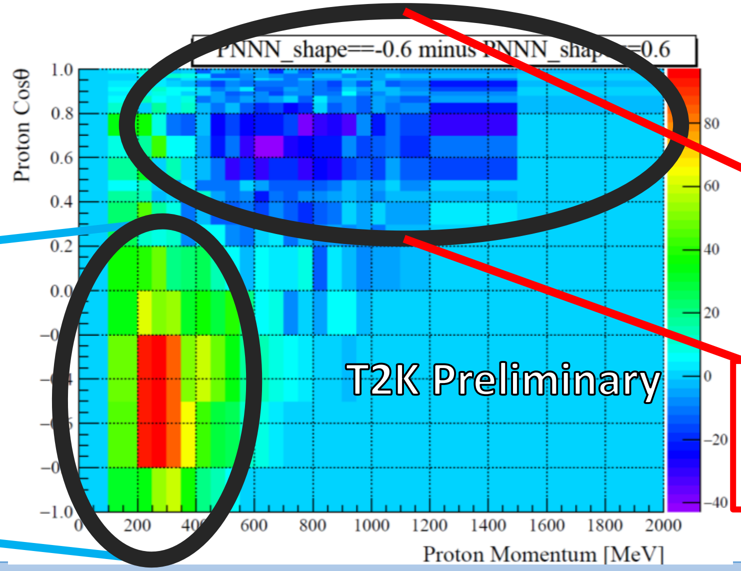
Two Particles Two Holes (2p2h)

- Better description of 2p2h pn/nn pairs contribution









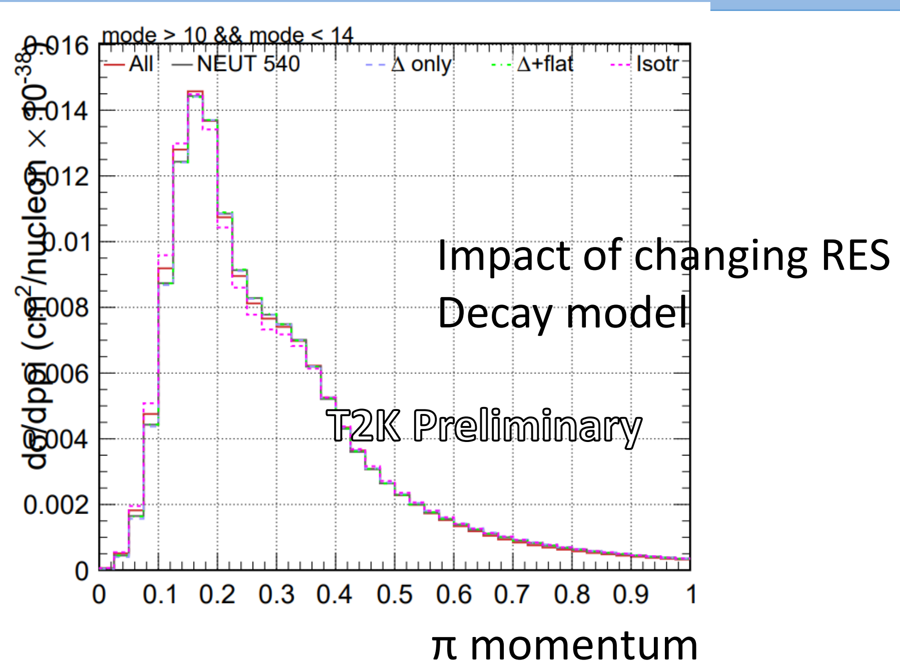
Increase of **nn** shifts events to lower momentum, higher angles.

Increase of **pn** shifts events to higher momentum, forward going protons.

RES and DIS

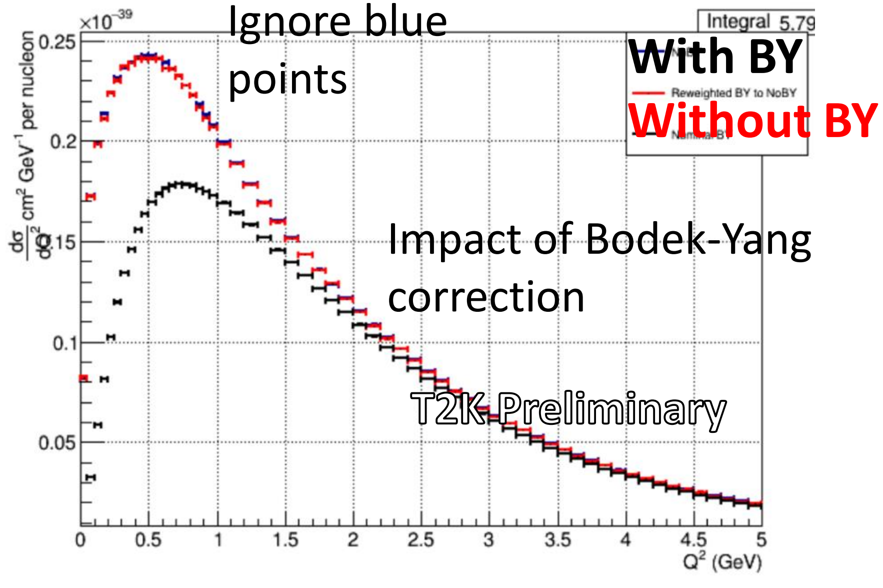
Resonant Scattering (**RES)**

- New tune of bubble chamber data to resonance model parameters
- New resonance decay uncertainties
- Effective inclusion of binding energy for Resonant channel



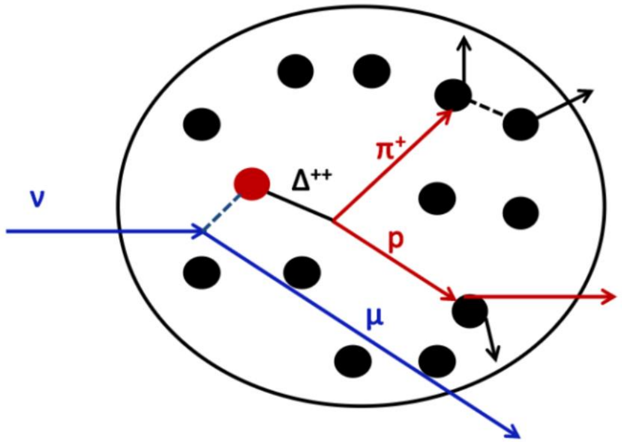
Deep Inelastic Scattering(**DIS)**

- New multi-π uncertainty varying shape of hadronic mass *W* and *π* multiplicity
- Improved Bodek-Yang parameterization. BY is introduced as QCD becomes non-perturbative at low Q2.



Final State Interactions

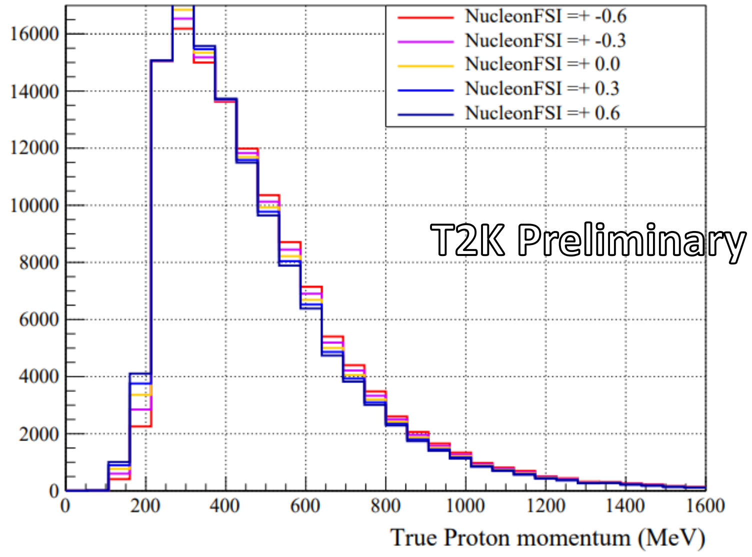
Final State Interactions – interactions that produced particles can undergo inside nucleus.

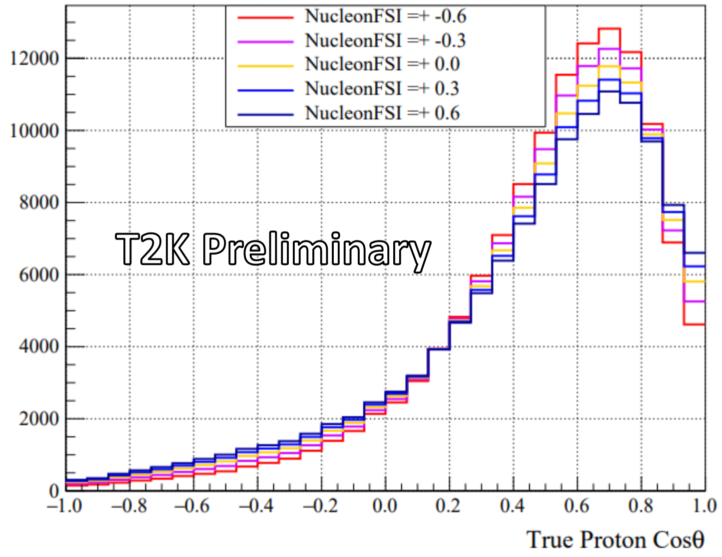


For example, pion produced in **RES** can be absorbed. Pion can also change its charge or eject nucleon.
Proton can eject neutron or another proton.

FSI can highly alter what we see in experiments, this can result in wrongly evaluating cross-section for given interactions.

New Nucleon (**FSI**) uncertainty added this year.

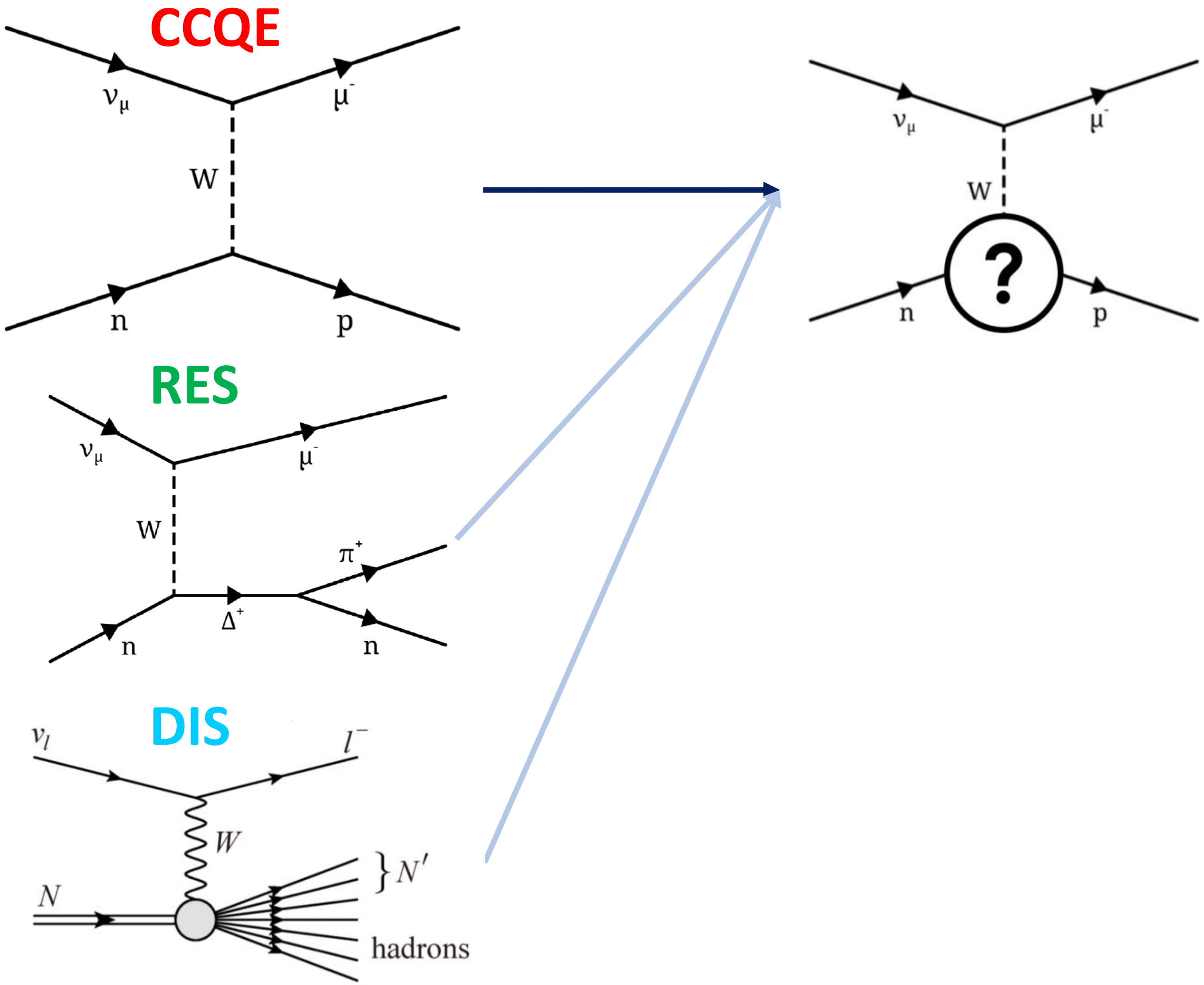




What is Topology

Interaction Mode

Interaction Topology



CC0π (CCQE-like)

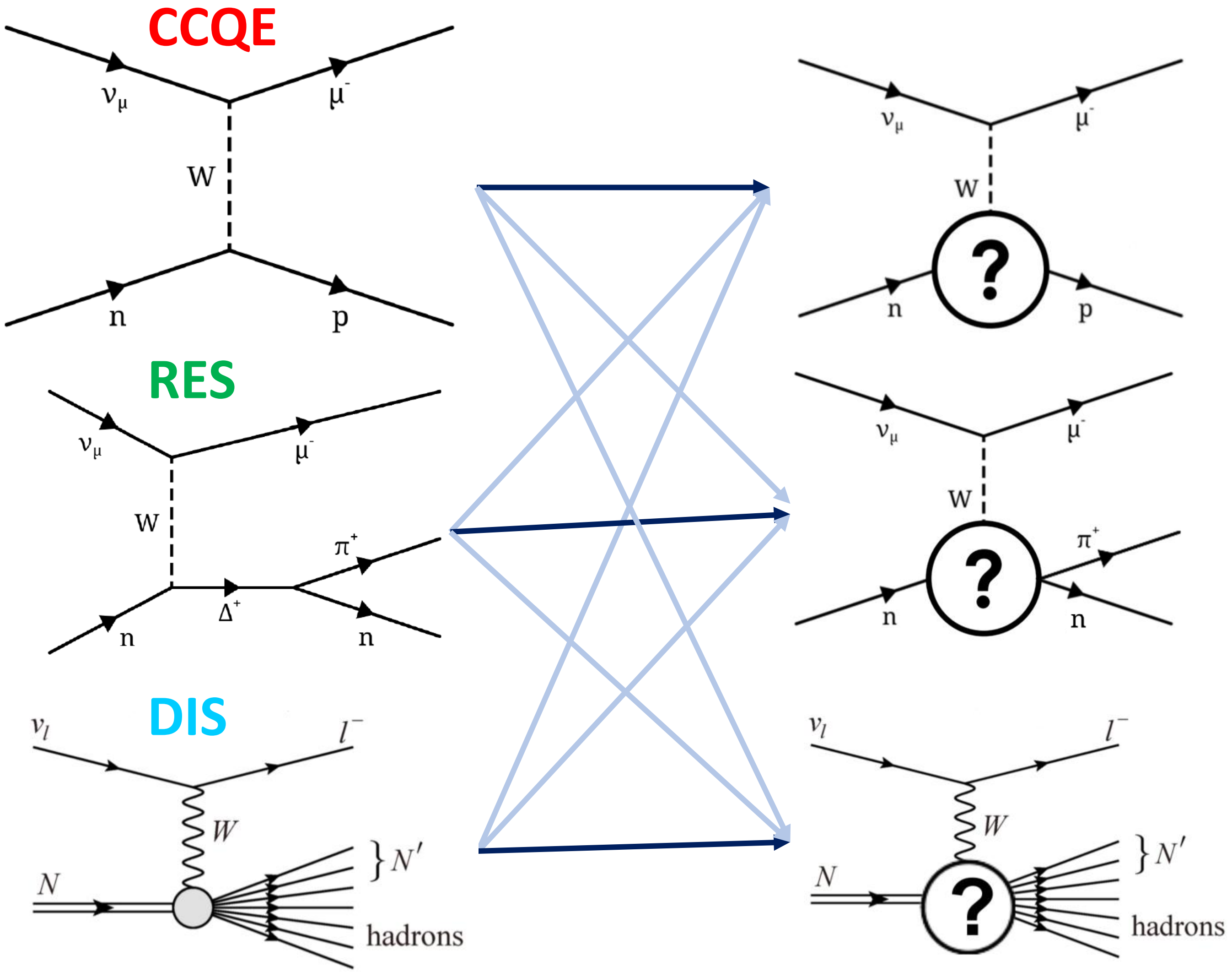
Due to physical effect as well as reconstruction what we observe in the detector doesn't have to be exactly what really happened.

We differentiate between:

- **Interaction Mode** (that truly happened)
- **Interaction Topology** (what we observed)

ND280 Samples

Interaction Mode **Interaction Topology**



CC0π (CCQE-like)

CC1π (RES-like)

CCOther (DIS-like)

Due to physical effect as well as reconstruction what we observe in the detector doesn't have to be exactly what really happened.

We differentiate between:

- **Interaction Mode** (that truly happened)
- **Interaction Topology** (what we observed)

In T2K we divide data into different samples which correspond to **Topology.**

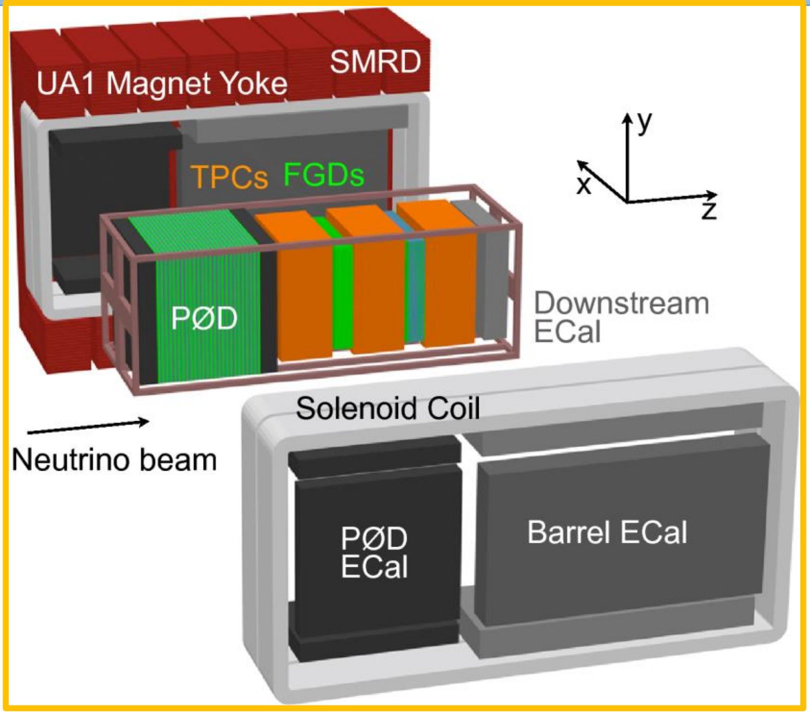
FGD1 and FGD2

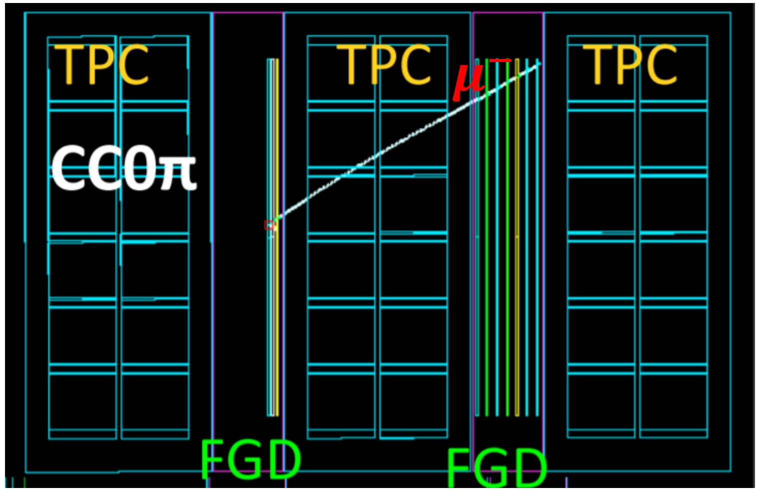
ND280 has two interaction targets which are organic scintillator detectors:

FGD1 is hydro-carbon detector
FGD2 is hydro-carbon with water layers. Since FD is filled with ultra-pure water and some parameters are different for carbon and oxygen, we need FGD2 samples to better constrain them.

TPCs are time projection chambers with finer granulation compared to **FGD**. We only consider muons which traveled to at least one TPC.

FGDs and TPCs (tracker) are surrounded by the **ECal**.

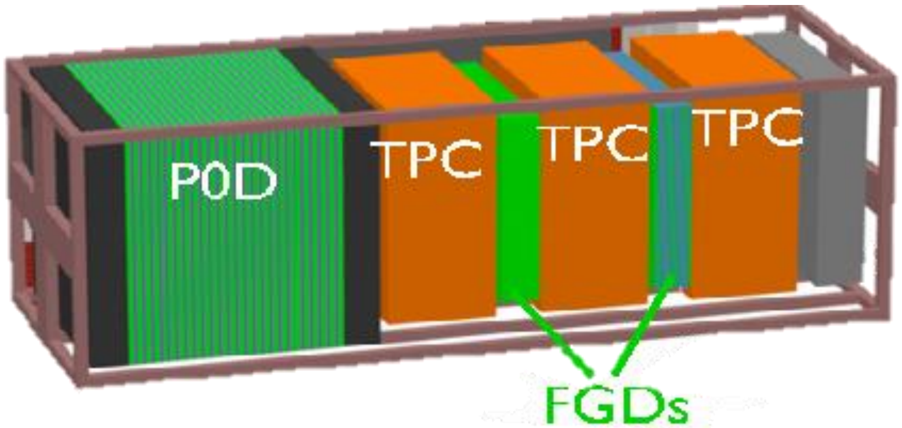




ND280 Samples

In **2020** analysis ND280 used **18** samples

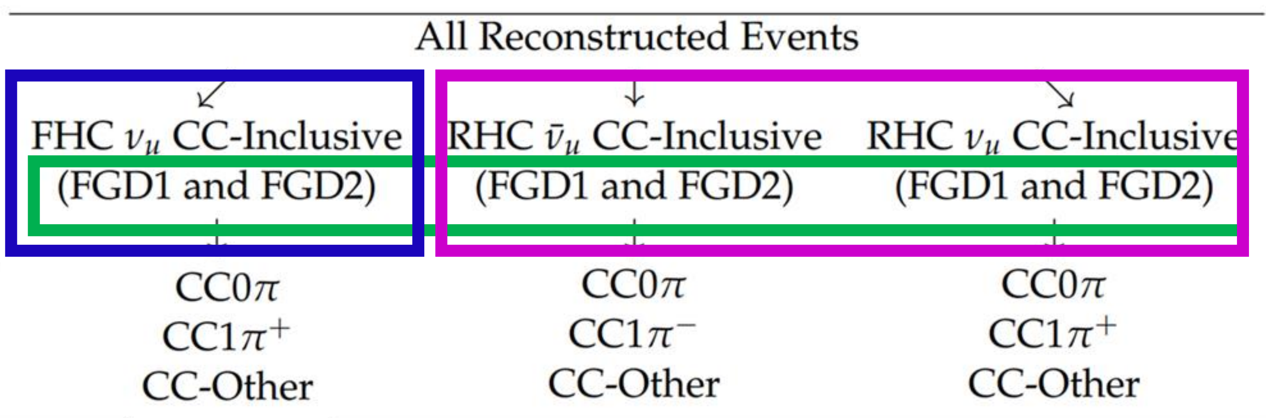
ND280 has two targets:
FDG1 (9 samples) and FGD2 (9 samples).



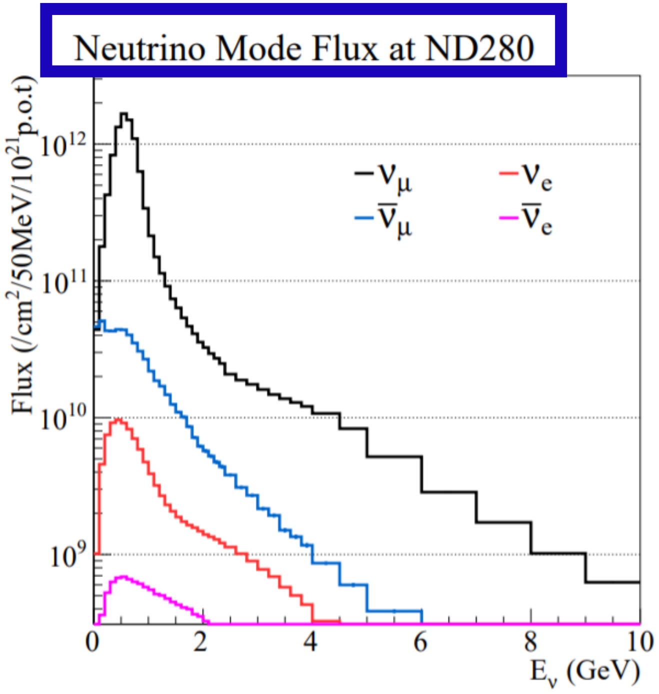
We have 6 samples in neutrino mode.

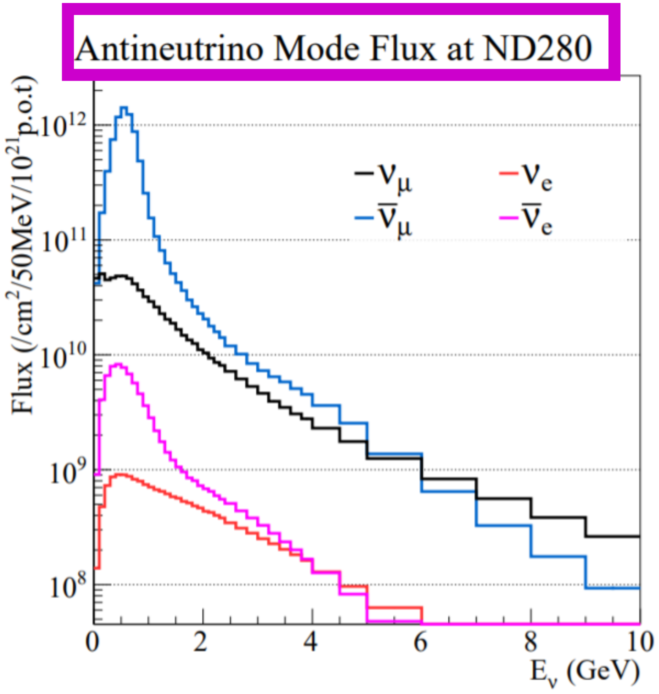
And 12 samples in antineutrino.
Because of $\nu_\mu$contamination, we have signal and background samples.

Several things changed since 2020.



Forward Horn Current (**FHC**) - ν mode
Reverse Horn Current (**RHC**) - $\bar{\nu}$ mode

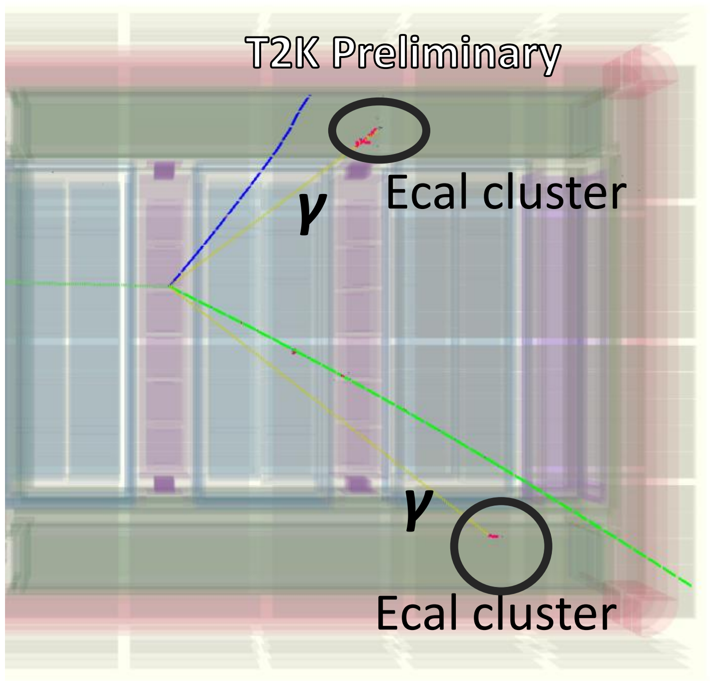




CC Photon

π^0 are important background at Far Detector and can originate from several processes.

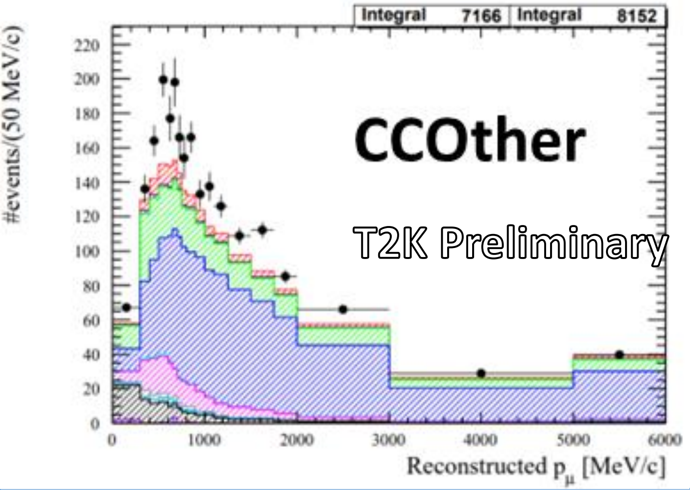
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\eta \rightarrow \pi^0 + X \rightarrow \gamma + \gamma + X$$
$$\eta \rightarrow \gamma + \gamma$$
$$\Lambda \rightarrow \pi^0 + X \rightarrow \gamma + \gamma + X$$
$$K \rightarrow \pi^0 + X \rightarrow \gamma + \gamma + X$$

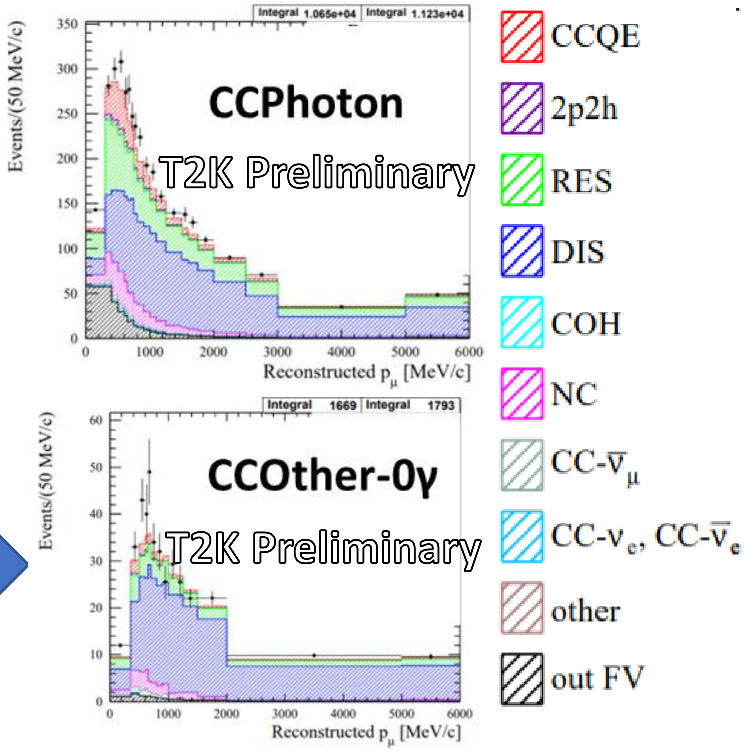


New CC Photon sample takes into account events with reconstructed photon object in the ECal.

This sample has been only included in **neutrino mode**.

There is ongoing work for antineutrino photon sample.





New sample is a mix bag of different processes.

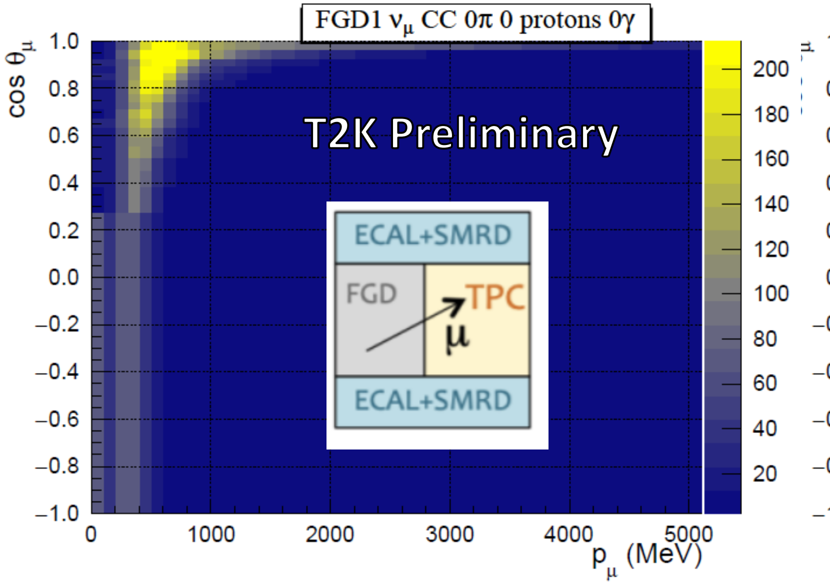
The biggest advantage of this sample is making CC Other more enhanced with **DIS** events

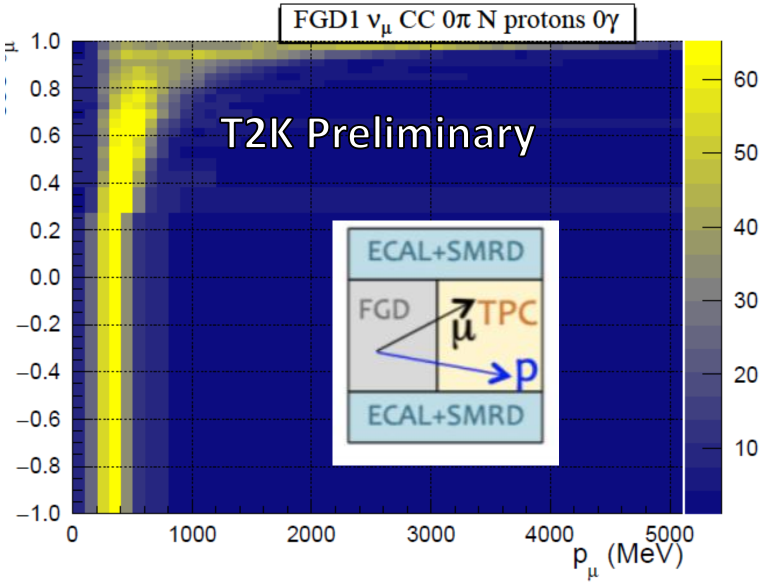
Proton Samples

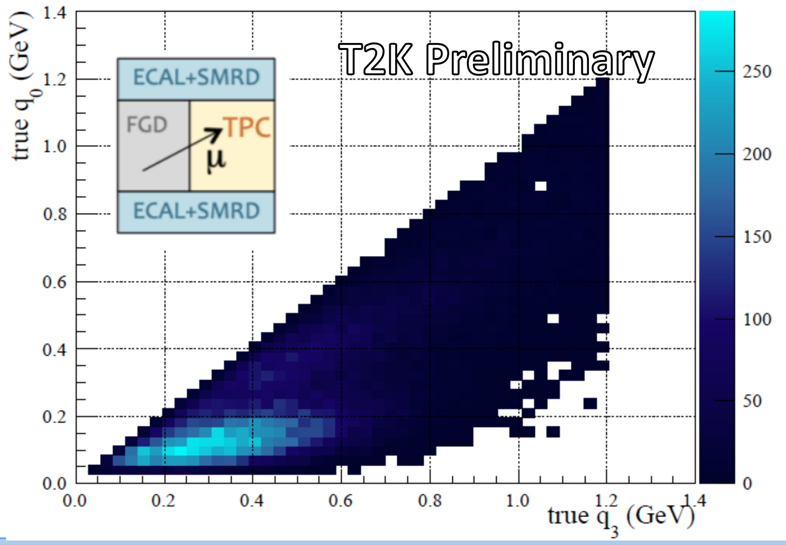
Previous CC0pi sample has been split into:

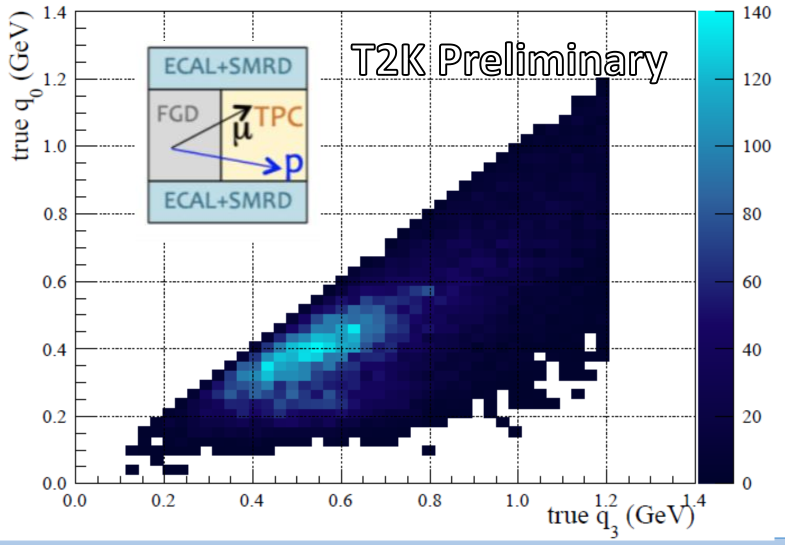
CC0pi-0p – no protons
CC0pi-Np – at least one proton

	CC0Pi	CC0Pi-0p	CC0Pi-Np
	Fraction %	Fraction %	Fraction %
CCQE	51	58	38
2p2h	11	10	11
RES	23	19	30
Other	15	13	21









Proton-tagged samples have been implemented only in neutrino mode.

Energy transfer:

$q_0 = E_\upsilon - E_\mu$

Momentum transfer:

$|\vec{q}_3| = |\vec{p}_\upsilon| - |\vec{p}_\mu|$

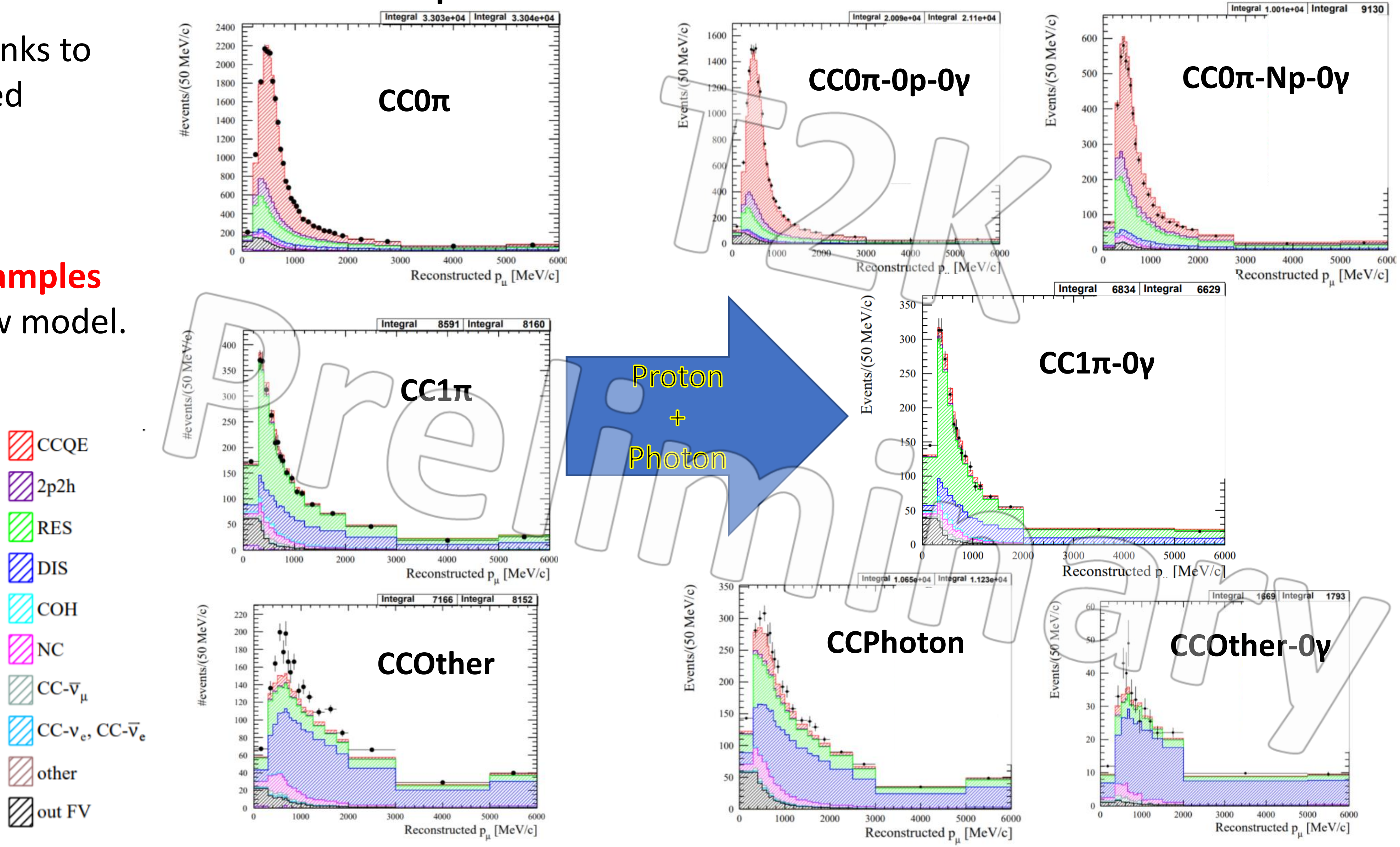
New samples at the near detector

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

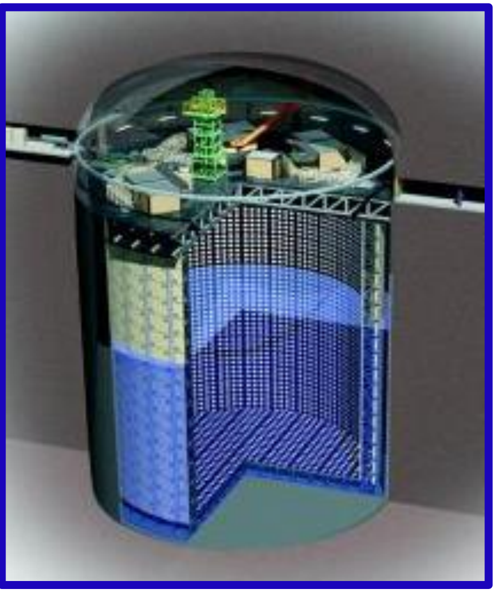
- **proton and photon samples** help better probe new model.

Total number of ND samples 18→22

2020 Samples | **2022 Samples**



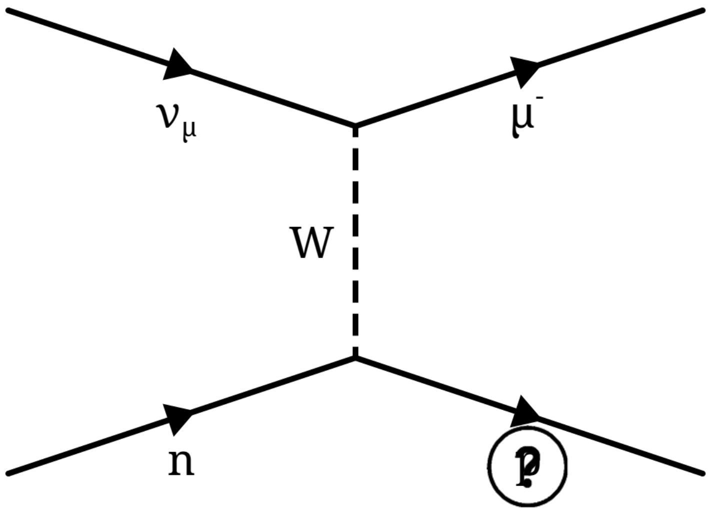
Far Detector Samples

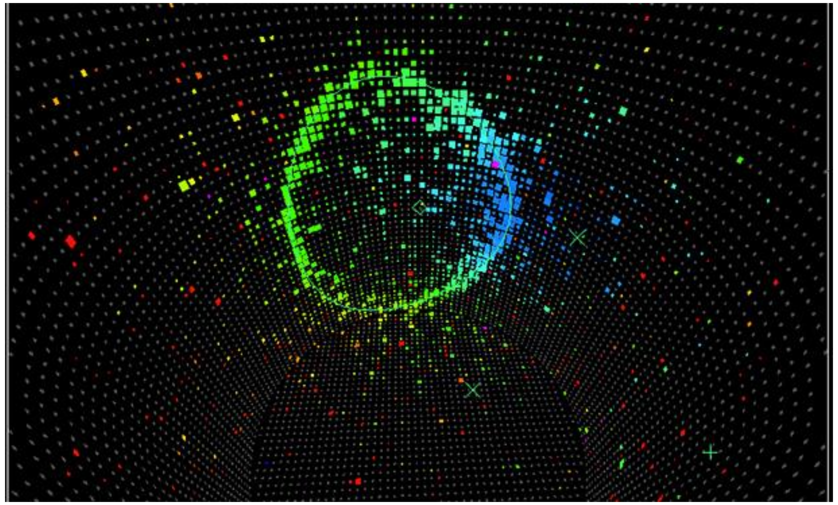


Super-Kamiokande (SK) is a water Cherenkov detector.

Cherenkov threshold of 1.04 GeV/c for protons, meaning most protons below threshold.

Energy reconstruction using alternative method.

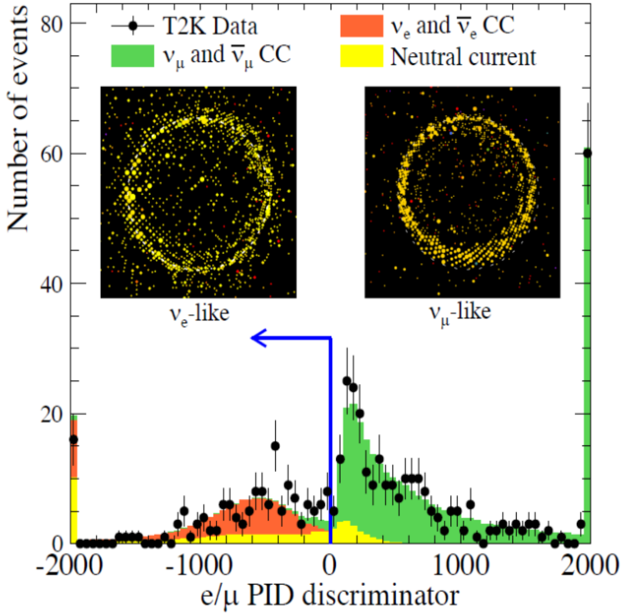




$$E_{\upsilon}^{rec} = \frac{m_p^2 - (m_n - E_B)^2 - m_e^2 + (m_n - E_B)E_l}{2(m_n - E_B - E_l + p_l cos\theta_l)}$$

Only uses particle masses, lepton kinematics and nuclear model.

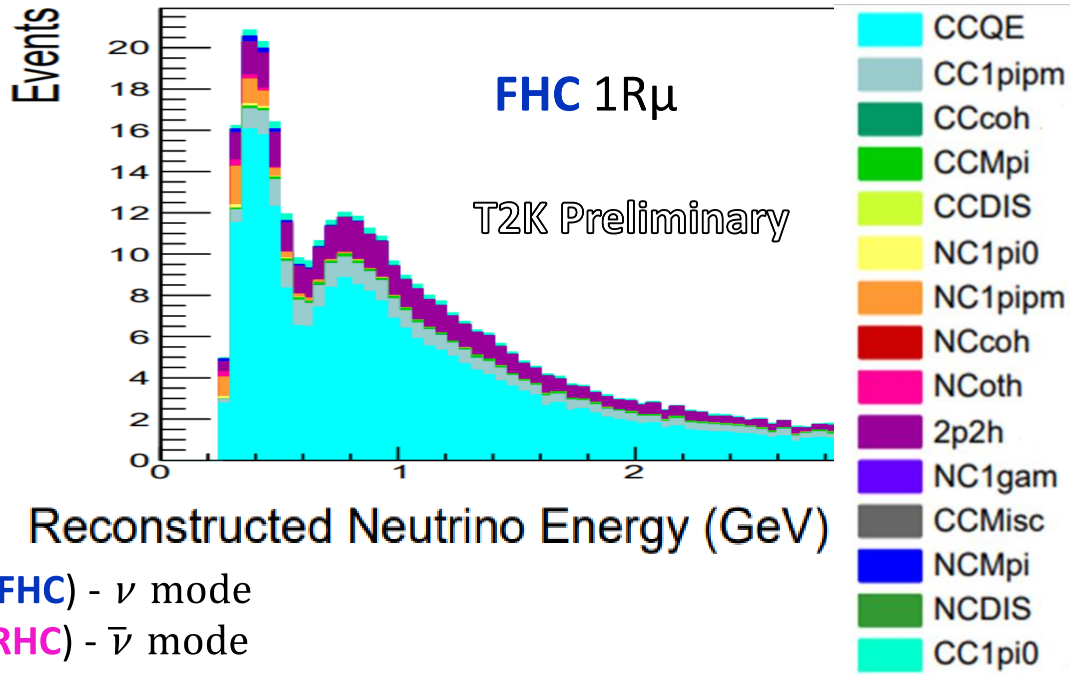
Super-Kamiokande Selection



Super-Kamiokande (SK) is dividing events into samples based on the number of reconstructed rings.

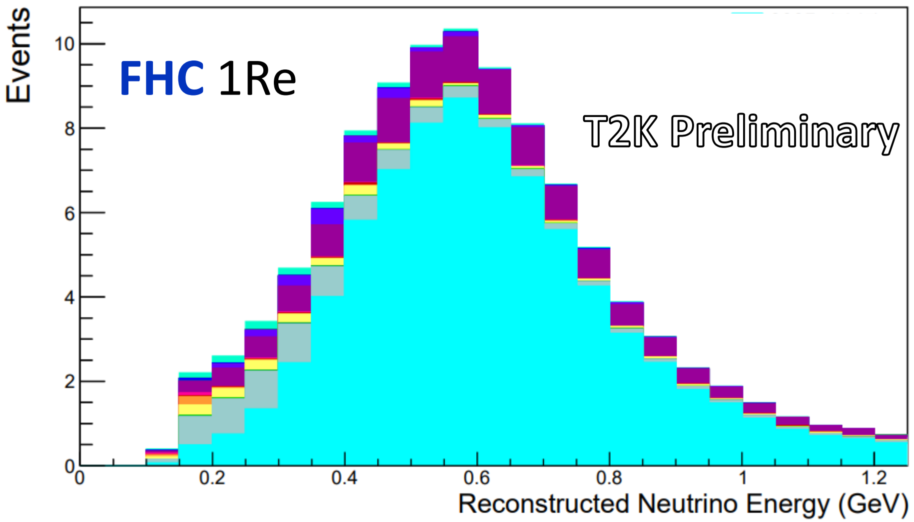
We can differentiate between rings based on its properties like shape.

A similar set of samples are for FHC and RHC.



Forward Horn Current (**FHC**) - ν mode
Reverse Horn Current (**RHC**) - $\bar{\nu}$ mode

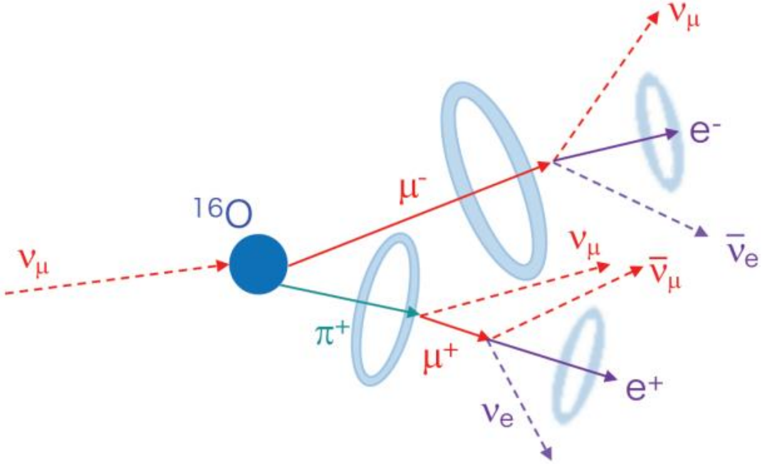
Mode	Sample Name	Description
$\boldsymbol{\nu}$	**1Re**	One e-like ring in $\boldsymbol{\nu}$ mode
	1Re CC1π+	One e-like ring and Michel electron in $\boldsymbol{\nu}$ mode
	1Rμ	One μ-like ring in $\boldsymbol{\nu}$ mode
	MRμ CC1π+ (Multi-Ring)	New! (next slide)
$\bar{\boldsymbol{\nu}}$	**1Re**	One e-like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



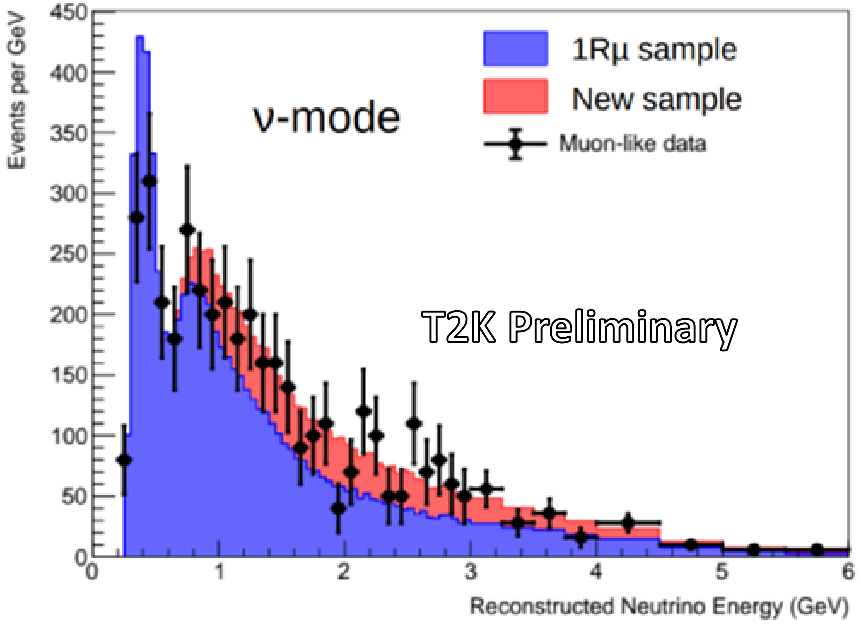
Multi-Ring Samples

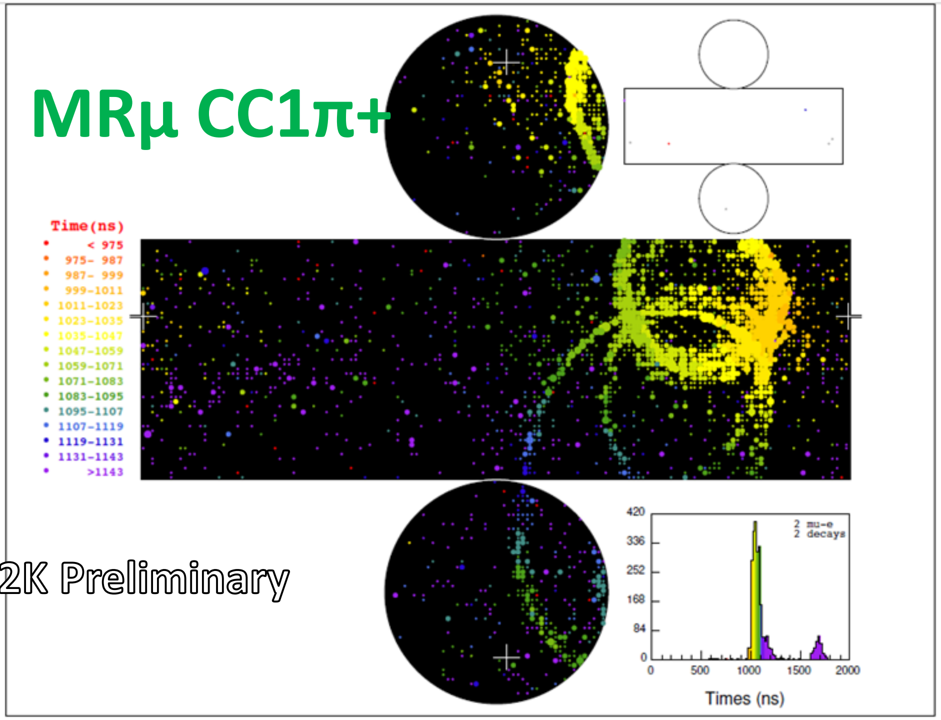
This analysis brings brand new sample for FHC only: **MRμ CC1π^+**:

- Two rings (1 μ^- and 1π^+) and Michel electron (from 1μ^-)
  or
- One 1μ^- ring and 2 Michel electrons (from 1μ^- and 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 to crosscheck if model is well under control.





Oscillation Analyses

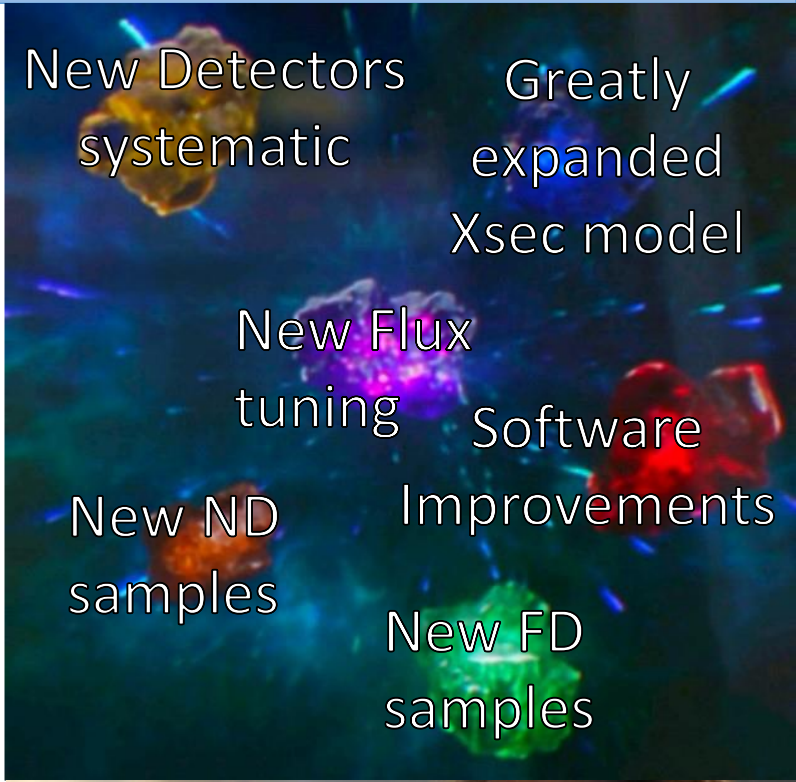
T2K uses two analysis frameworks using Poisson likelihood ($-\boldsymbol{logL}$) and gaussian penalty terms from our priors. ND additionally used MC statistical uncertainty following Barlow-Beeston* approach.

- **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 ($\sin^2\theta_{13} = 0.0220$ +/− 0.0007), here we show only results with reactor constraints.

*Comput. Phys. Commun. (1993)

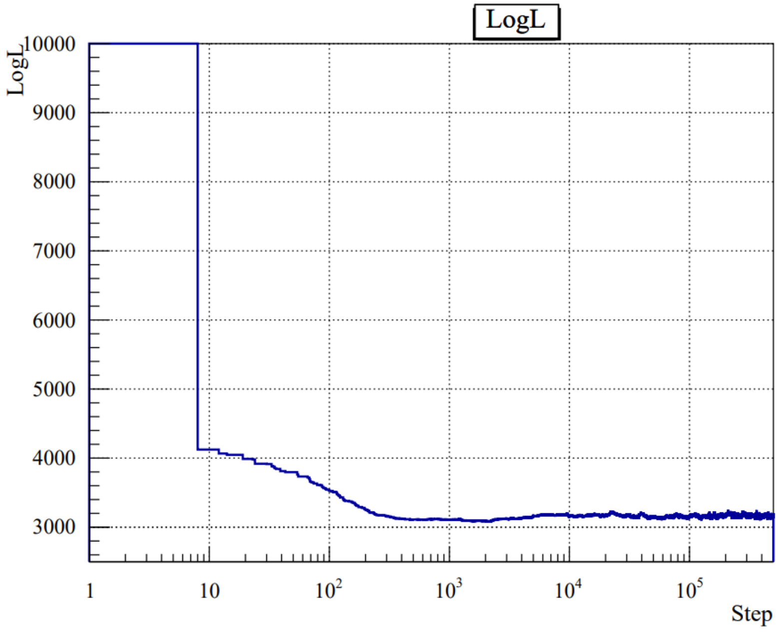


Log Likelihood

To find minimum we use log likelihood (LLH)

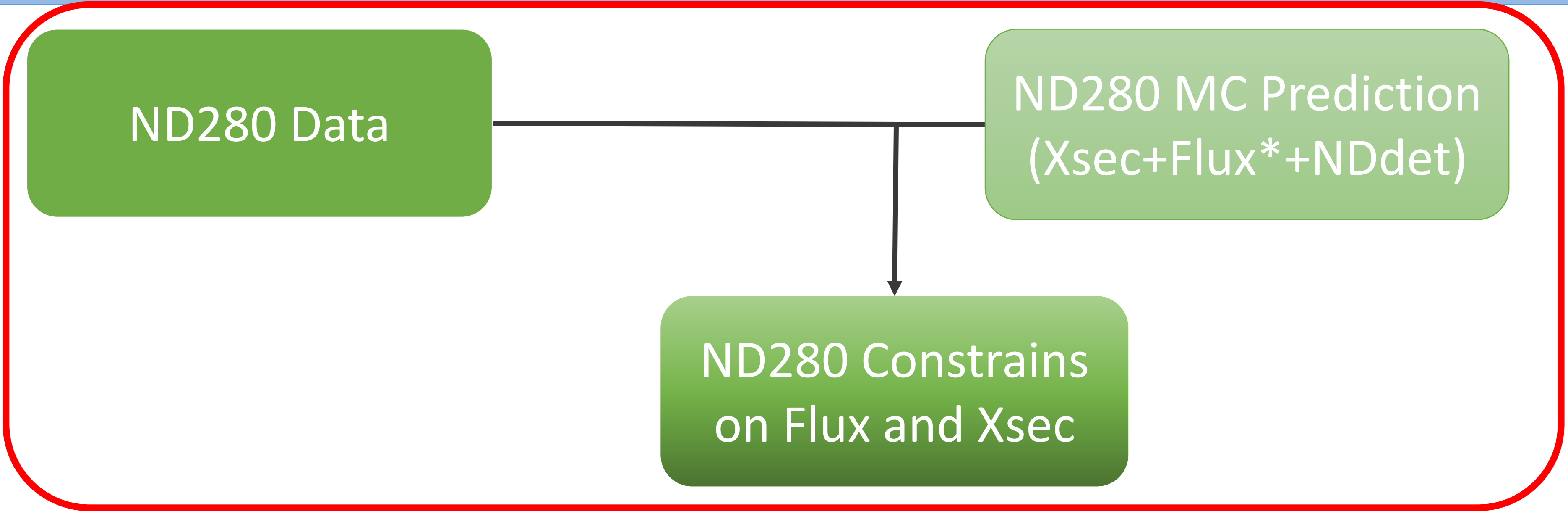
Poisson – account for data MC agreement
Barlow-Beeston – account for MC statistical uncertainty
Penalty term – account parameters prior uncertainty and correlations

$$\Delta\chi^2 = 2\sum_i \left[N_i^{\mathrm{MC}}(\vec{\theta}) - N_i^{\mathrm{data}} + N_i^{\mathrm{data}} \ln\left(\frac{N_i^{\mathrm{data}}}{N_i^{\mathrm{MC}}(\vec{\theta})}\right) + \frac{(\beta_i - 1)^2}{2\sigma_{\beta_i}^2}\right]$$
$$+ \sum_i^{E_\nu bins} \sum_j^{E_\nu bins} \Delta f_i \left(V_f^{-1}\right)_{i,j} \Delta f_j$$
$$+ \sum_i^{\mathrm{xsecpars}} \sum_j^{\mathrm{xsecpars}} \Delta \vec{x}_i \left(V_x^{-1}\right)_{i,j} \Delta \vec{x}_j$$
$$+ \sum_i^{\mathrm{ND280det}} \sum_j^{\mathrm{ND280det}} \Delta d^{\vec{N}D}_i \left(V_d^{-1}\right)_{i,j} \Delta d^{\vec{N}}$$



LLH for ND-only fit.

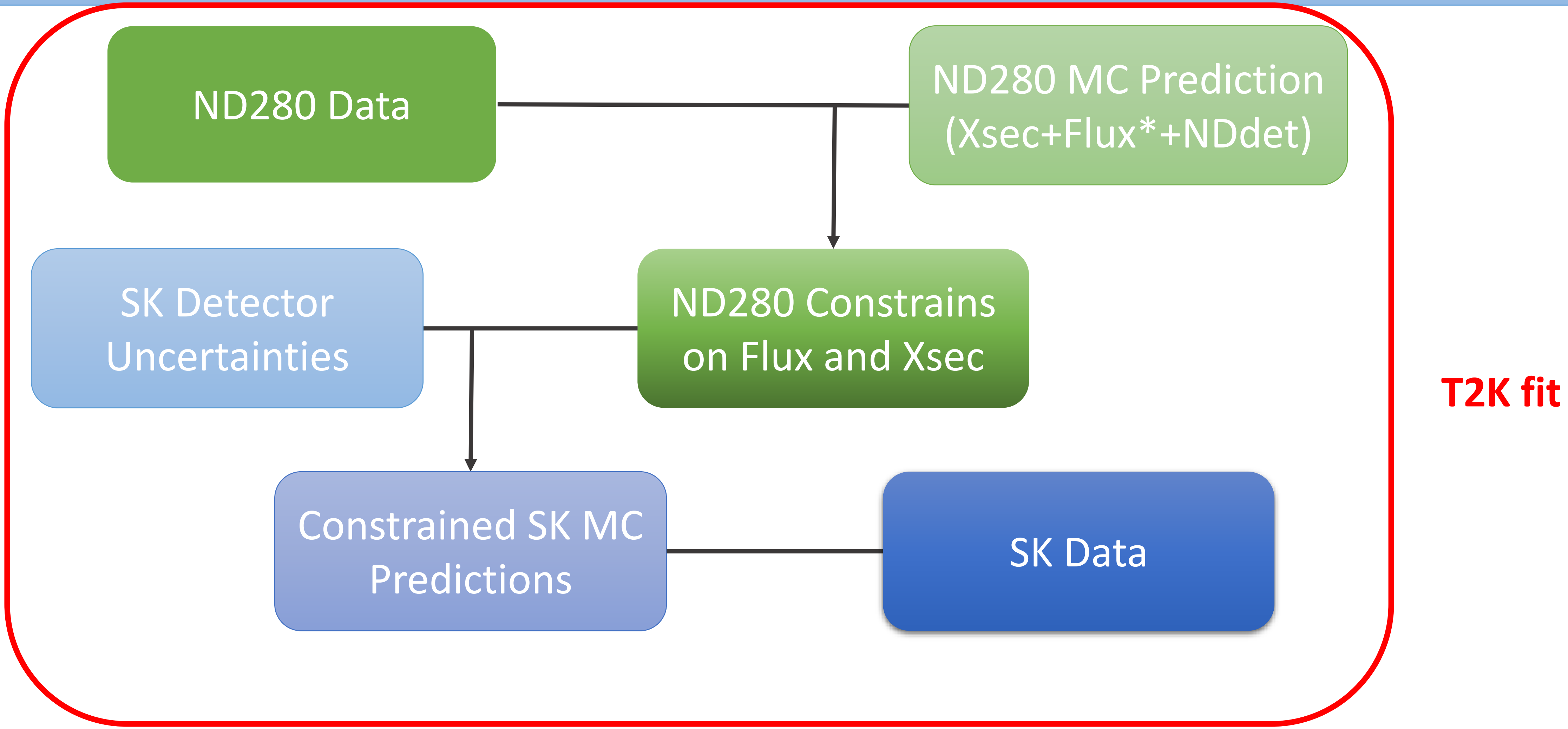
Consecutive ND+FD and Frequentist Approach



ND280 fit

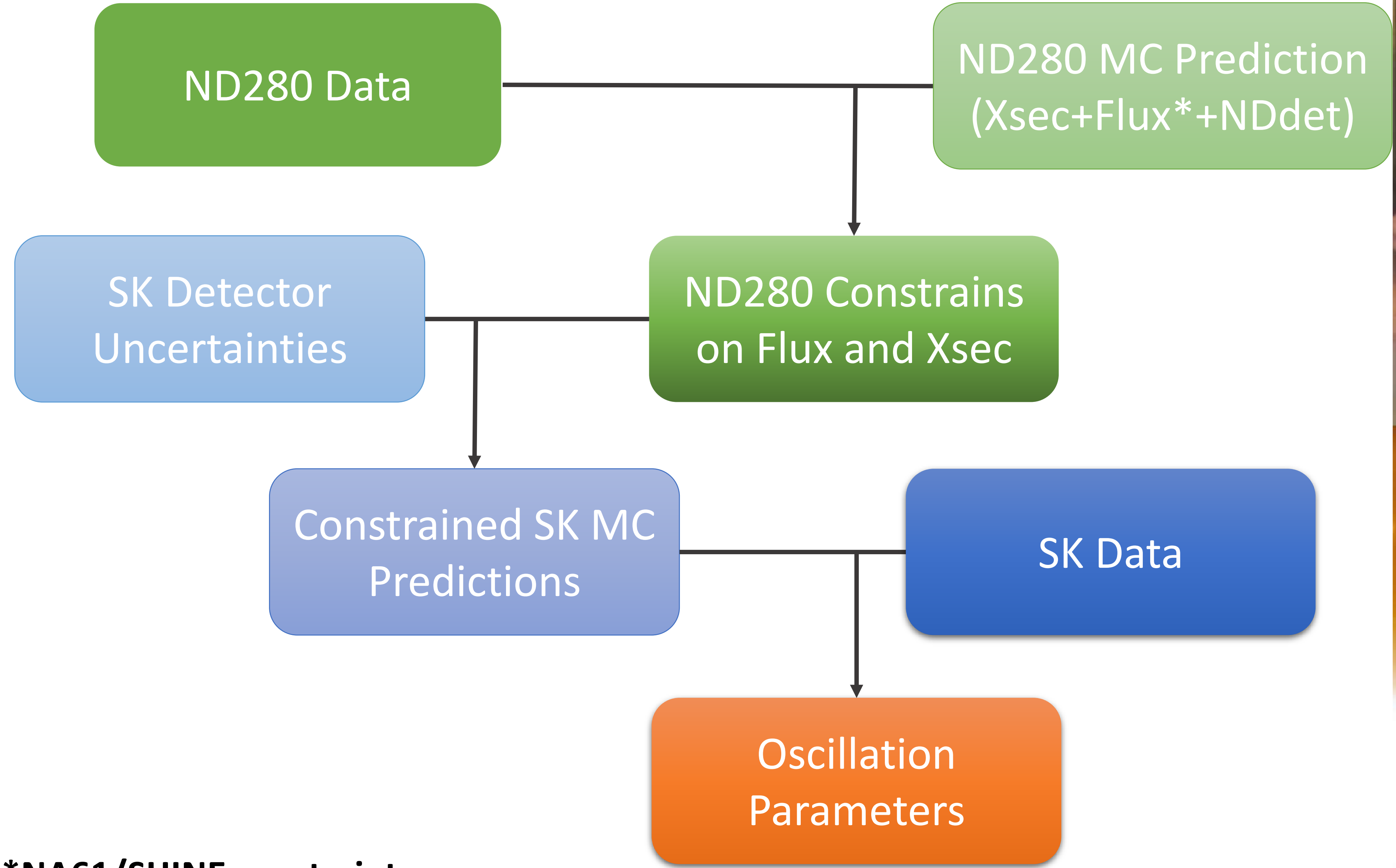
***NA61/SHINE constraints**

Consecutive ND+FD and Frequentist Approach



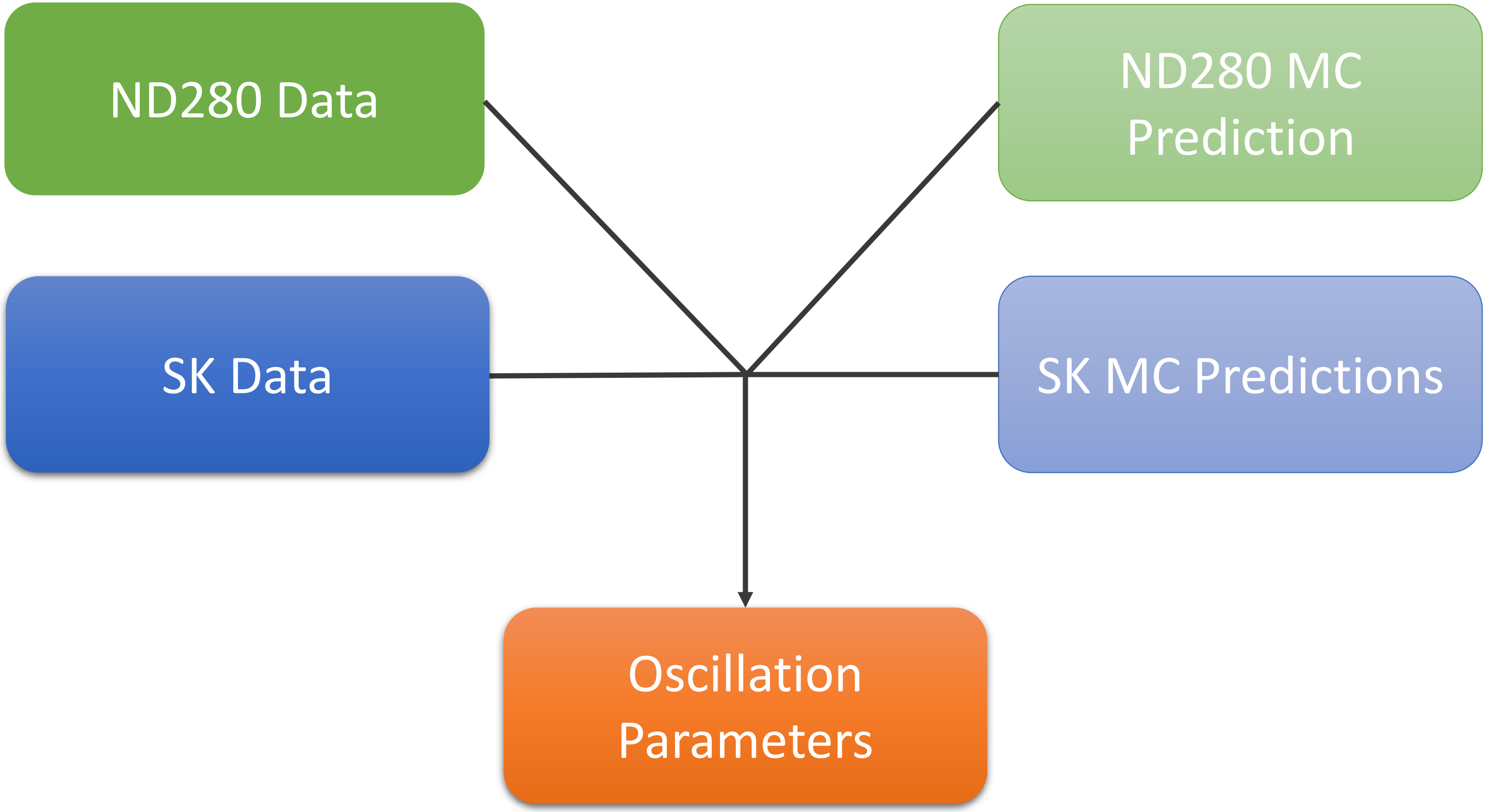
***NA61/SHINE constraints**

Consecutive ND+FD and Frequentist Approach



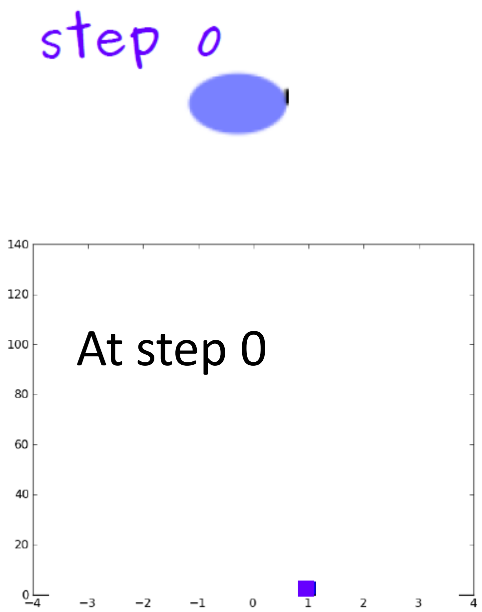
*NA61/SHINE constraints

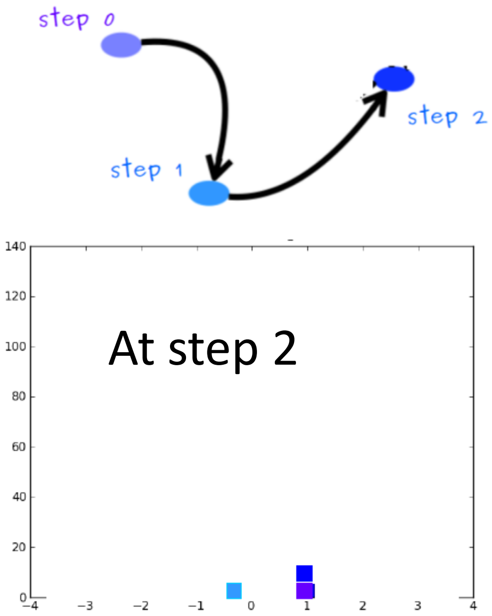
Simultaneous ND+FD and Bayesian Approach

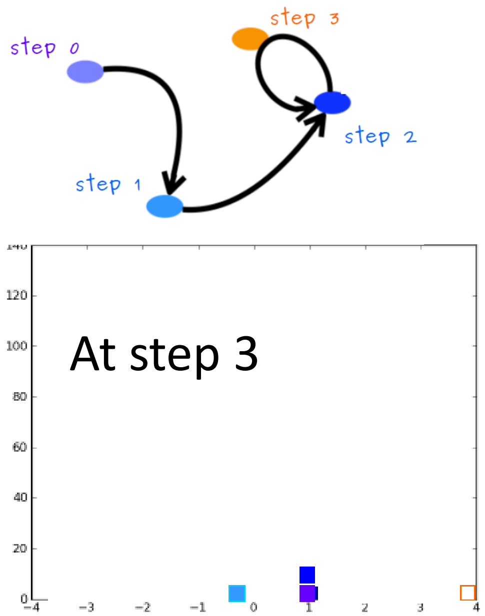


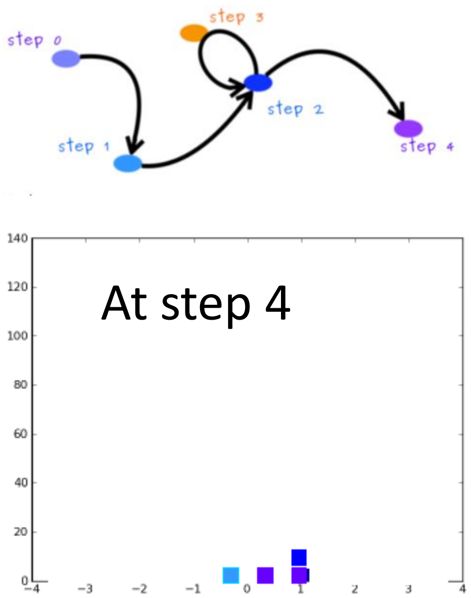
This group uses Markov Chain Monte Carlo (**MCMC**). Since I was involved in this group, I will discuss it in more details.

1D MCMC Visualization

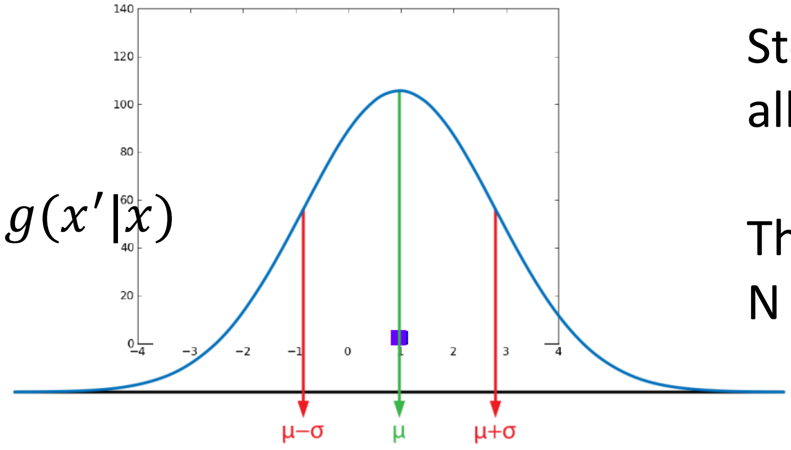






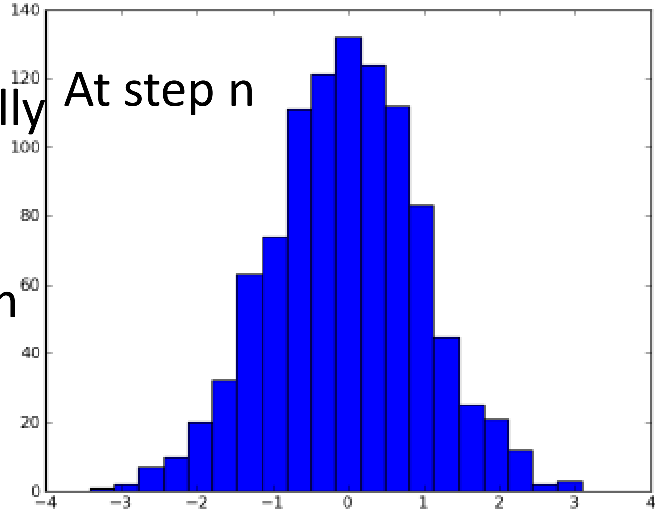


Let's assume proposal probability to be Gaussian.
Then we draw value x' from Gaussian.



Step is a value of parameter within some physically allowed range.

This is just an example in 1D, in ND fit we perform N dimensional walk.



Posterior Distribution

The main output from the MCMC is posterior distribution.

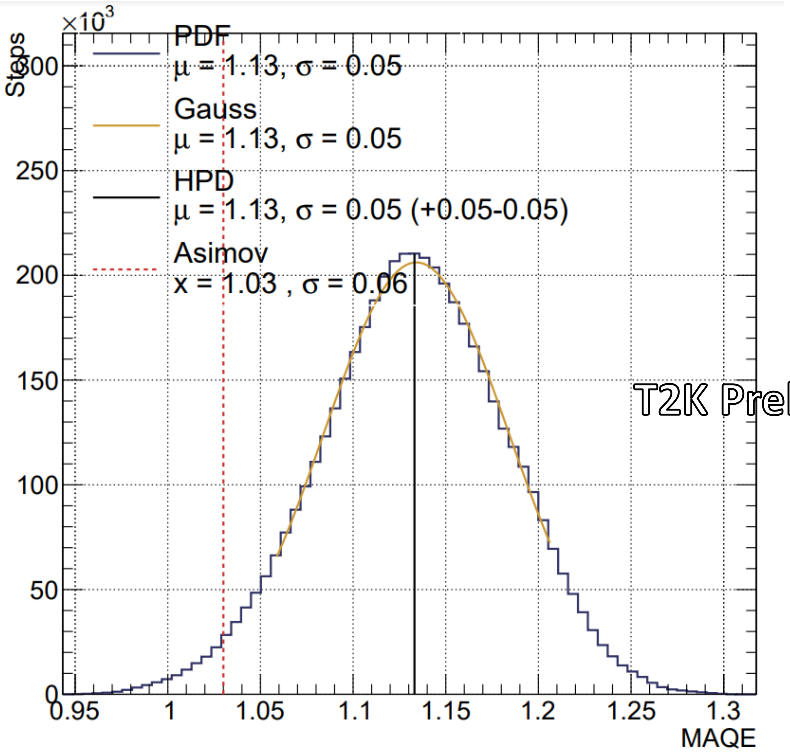
The peak of distribution can be associated with the „best fit" value and spread of distribution with the „error".

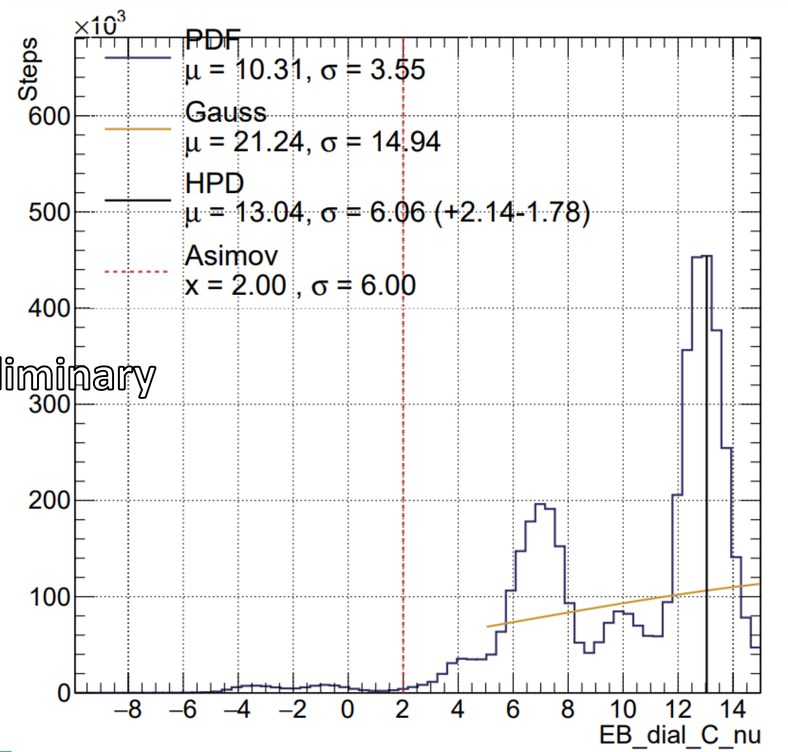
Posterior Distribution can have non-Gaussian shape. Taking them into account is advantage of Bayesian analysis with respect to Frequentist.

In Bayesian analysis we don't use best fit value to produce event rate spectra, rather Posterior Predictive Distribution of such quantity.

Bayes Theorem

$$\boxed{P(\vec{\theta}|Z)} = \frac{P(Z|\vec{\theta})P(\vec{\theta})}{P(Z)}$$

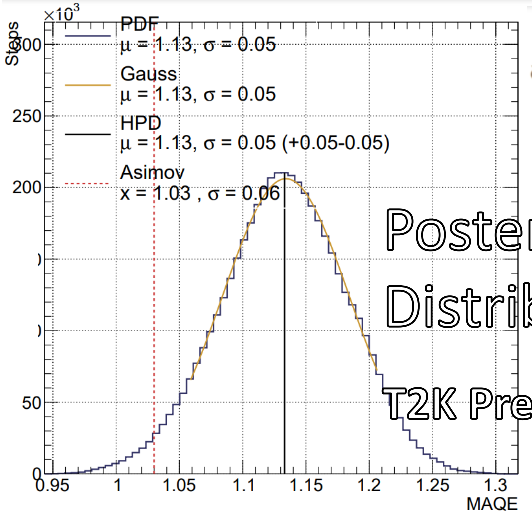


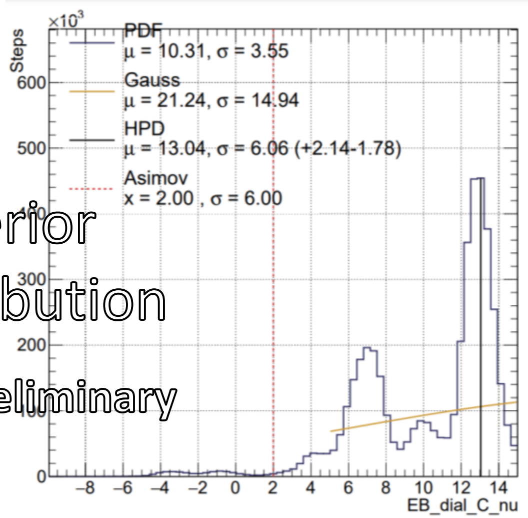


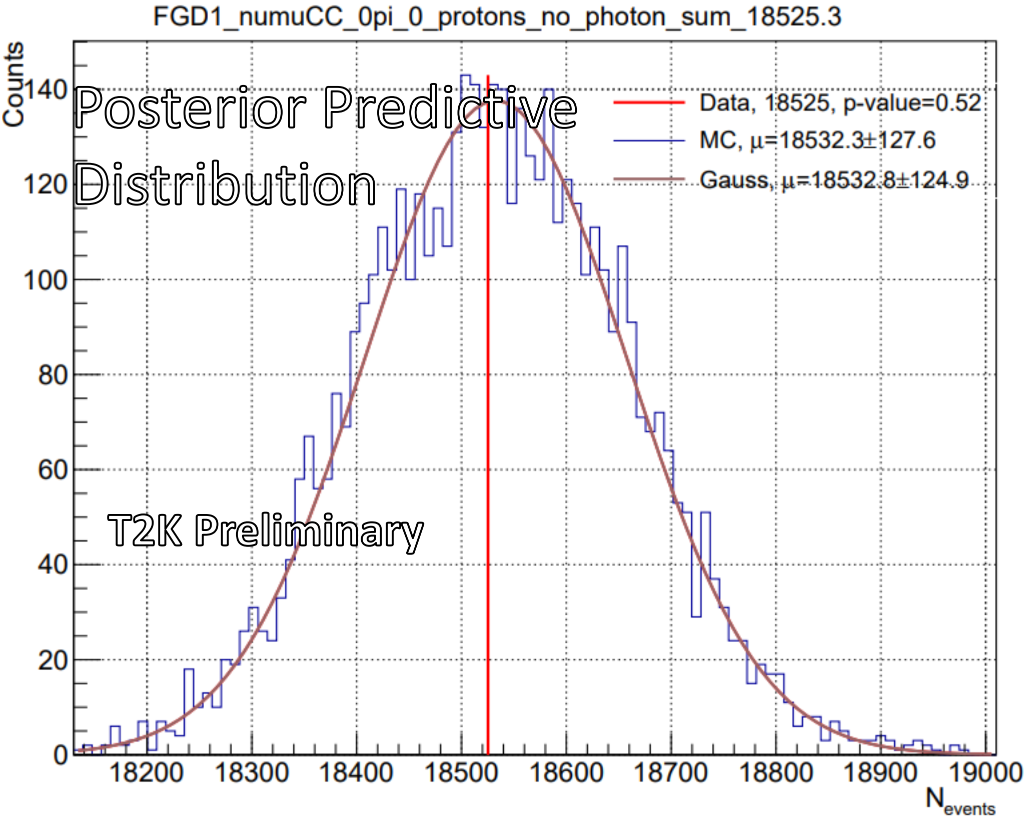
Posterior Predictive Distribution

We need to produce distribution of observables like number of events or muon momentum.

$$P(\vec{\theta}|Z) = \frac{P(Z|\vec{\theta})P(\vec{\theta})}{P(Z)}$$







We draw value for each parameter from posterior distributions.

Then we reweight MC creating so called toy experiment.

We create more toys, each time choosing new parameters. Then we plot the observable for all the toys and voila: this is Posterior Predictive Distribution.

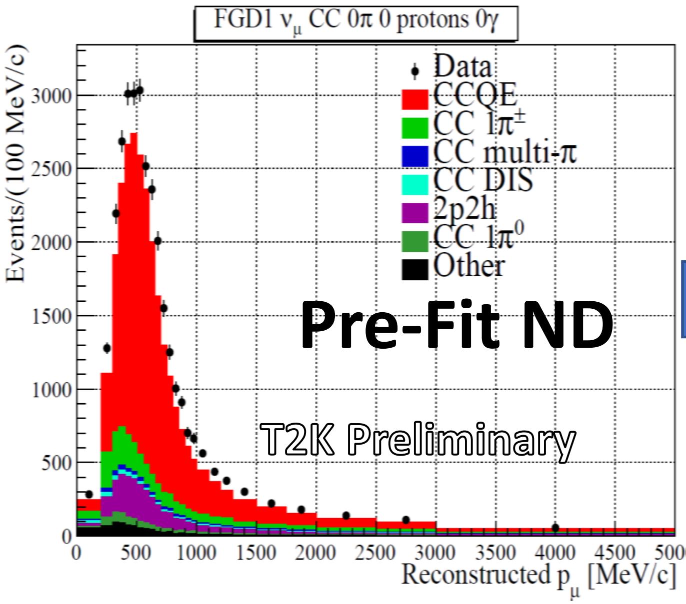
Impact of ND on FD

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

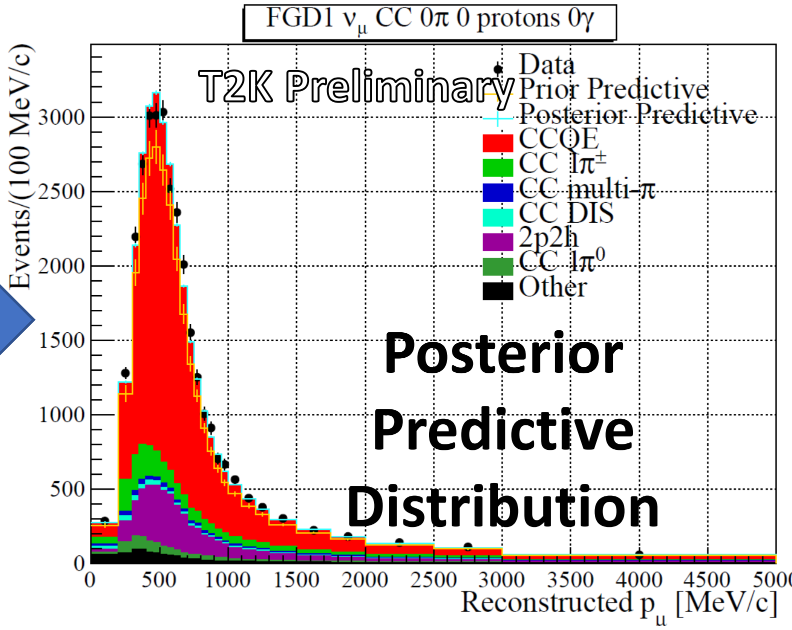
Most of cross-section and flux parameters are shared between ND280 and FD.

In final analysis we run simultaneous ND+FD fit, however for validation purpose in Bayesian approach we also perform ND only fits.

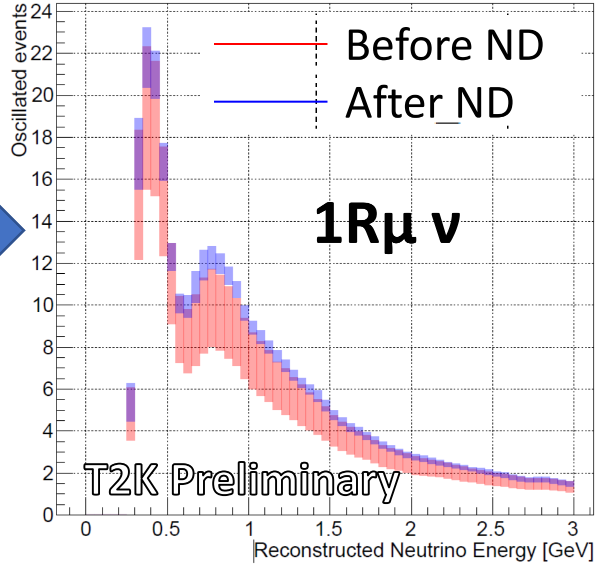
We can check Impact of ND only fit on predicted FD spectra.



Data Fit



Passing ND constraints to FD

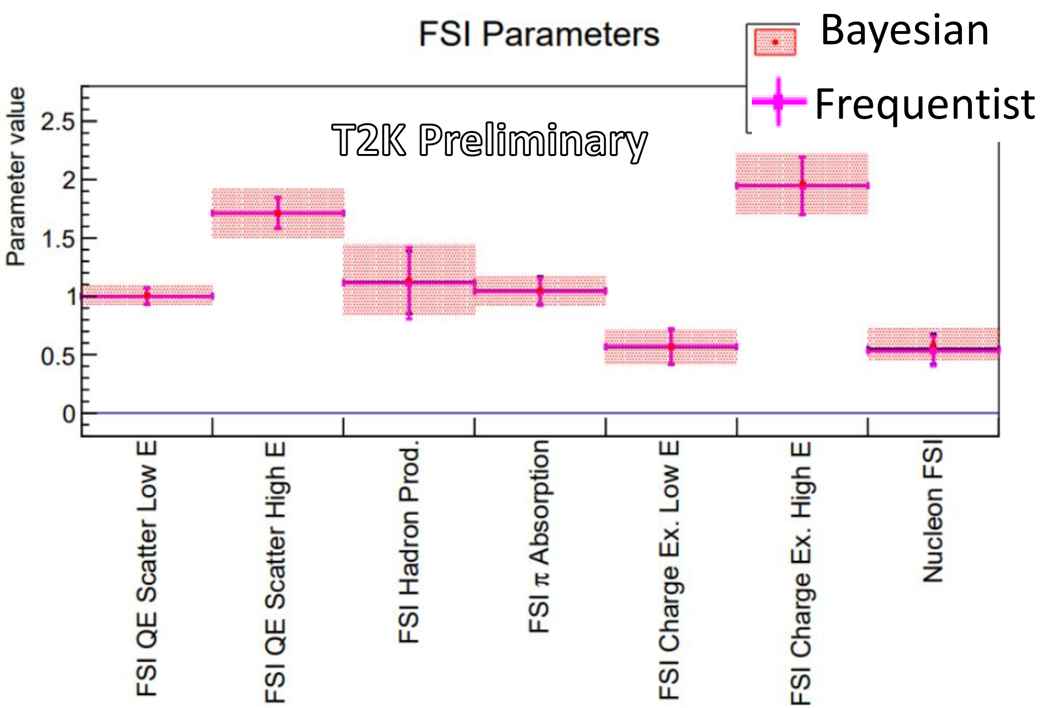


After propagating ND constrained parameters

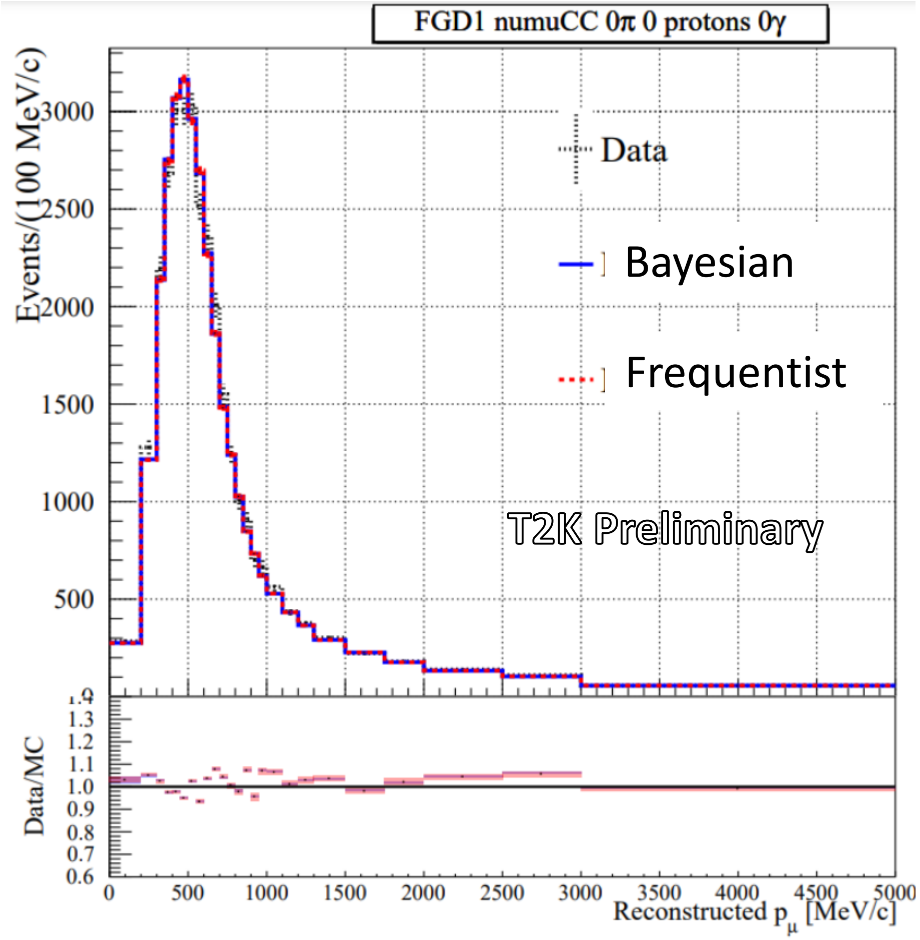
- Smaller error
- Spectrum shape changes, similar as in ND

Validation at ND280

Values of cross-section parameters from Frequentist and Bayesian ND280 analysis



Post fit spectra for Frequentist and posterior predictive for Bayesian aproaches.



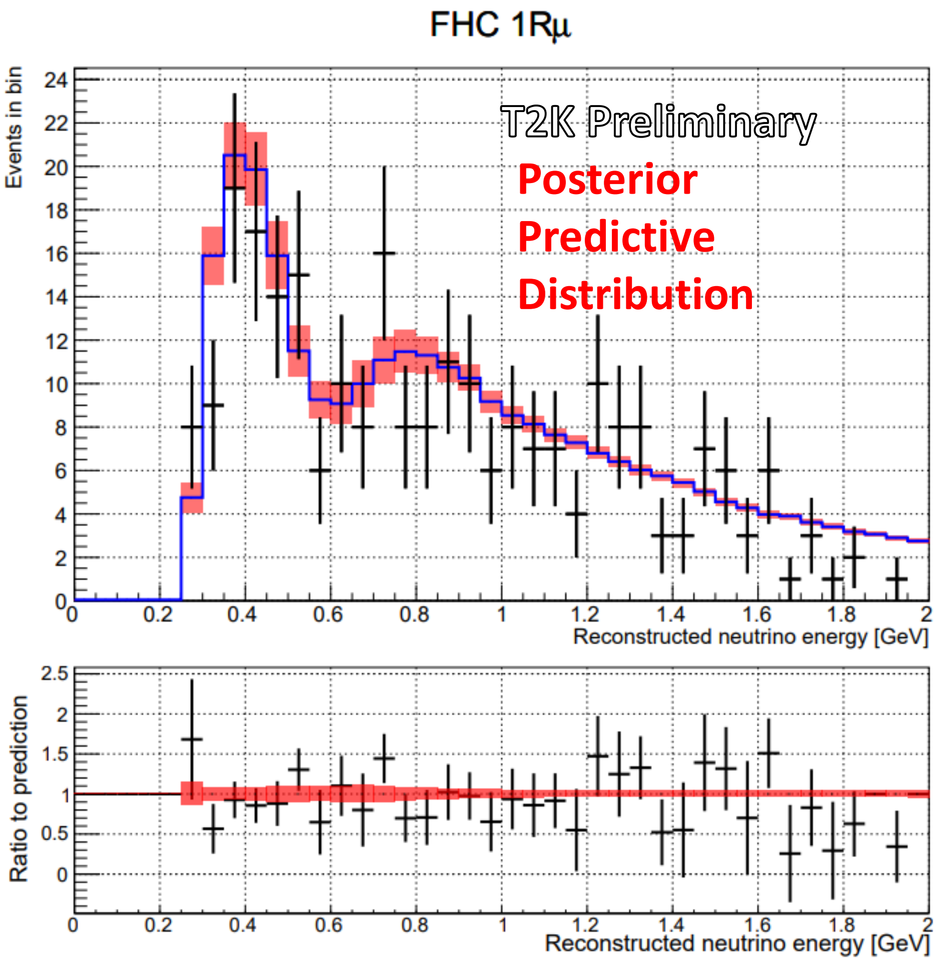
Despite of different approaches, both ND280 frameworks lead to very well agreeing results.

Now we can move to oscillation results

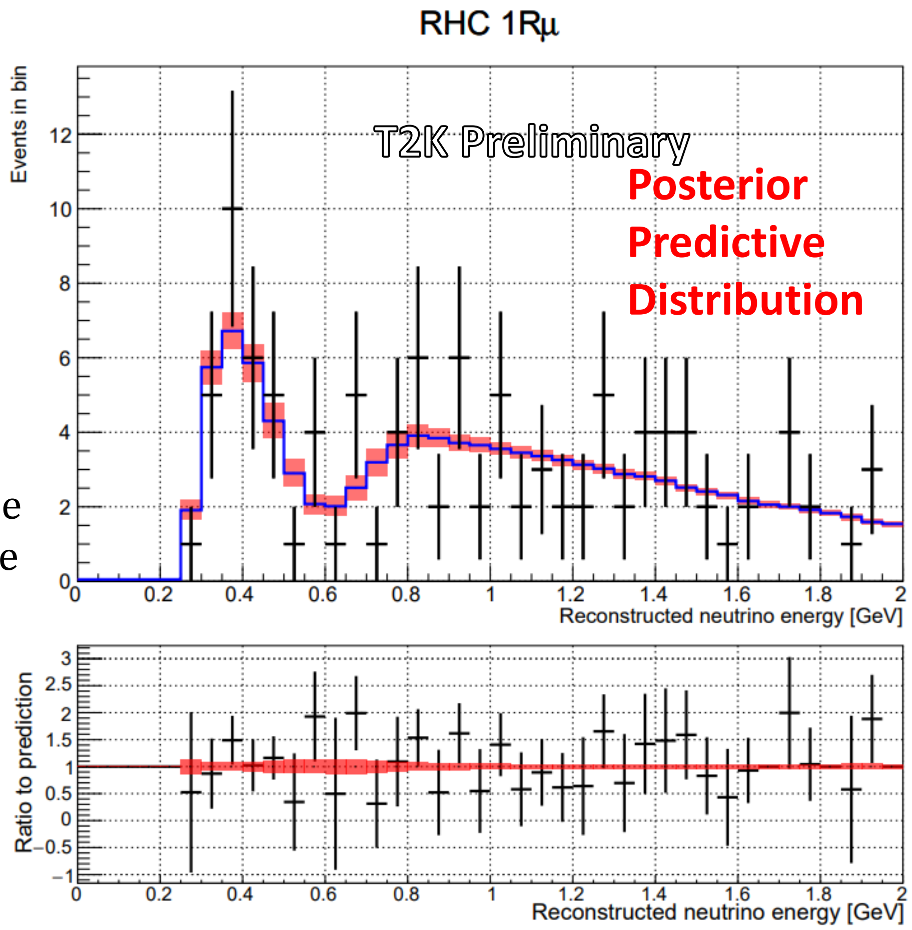
ND+FD Results

After ND+FD joint fit we obtain good agreement of data and MC.

Although the statistical error is quite high.



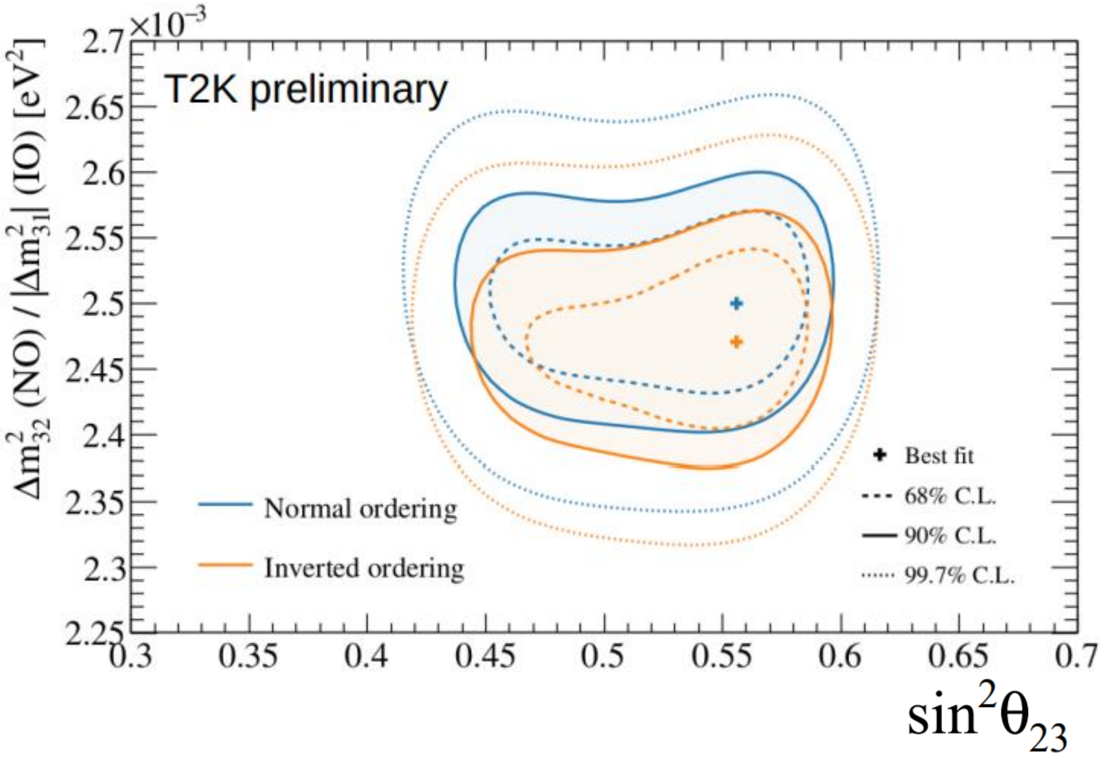
Forward Horn Current (**FHC**) - ν mode
Reverse Horn Current (**RHC**) - $\bar{\nu}$ mode



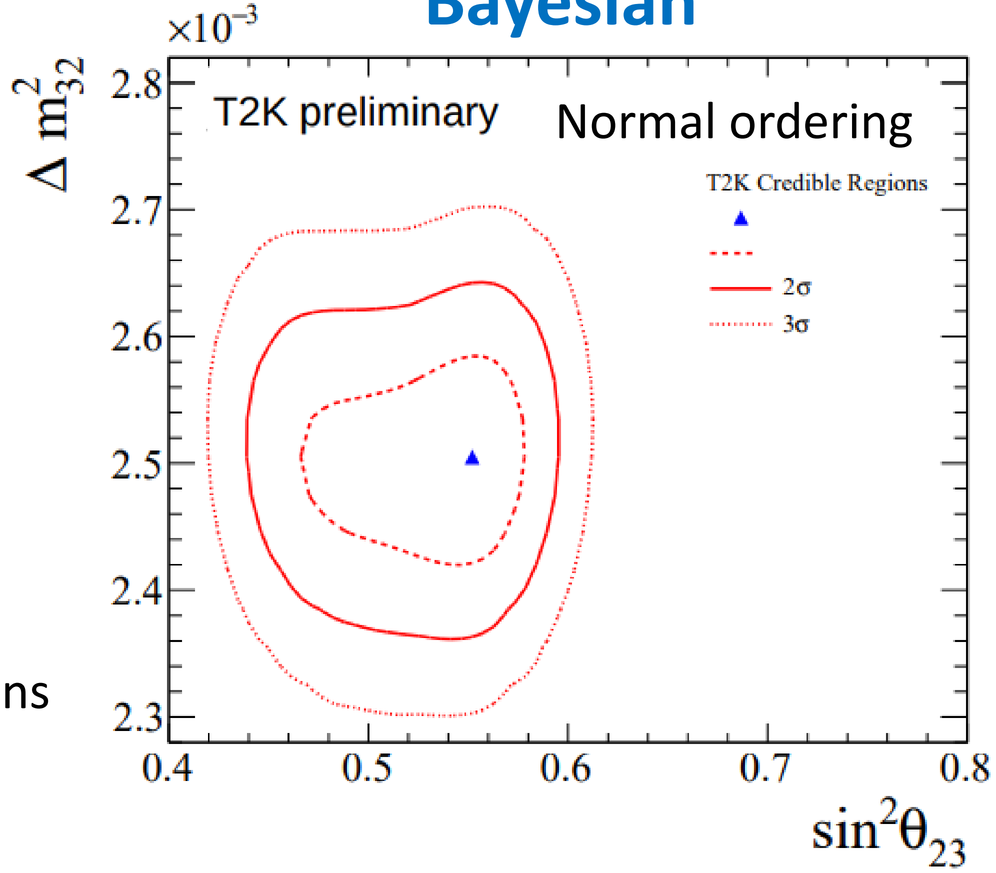
Atmospheric parameters

- Best fit point in the upper octant
- Lower octant still allowed at the 68% CL level
- Most precise measurement of θ_{23}

Frequentist



Bayesian

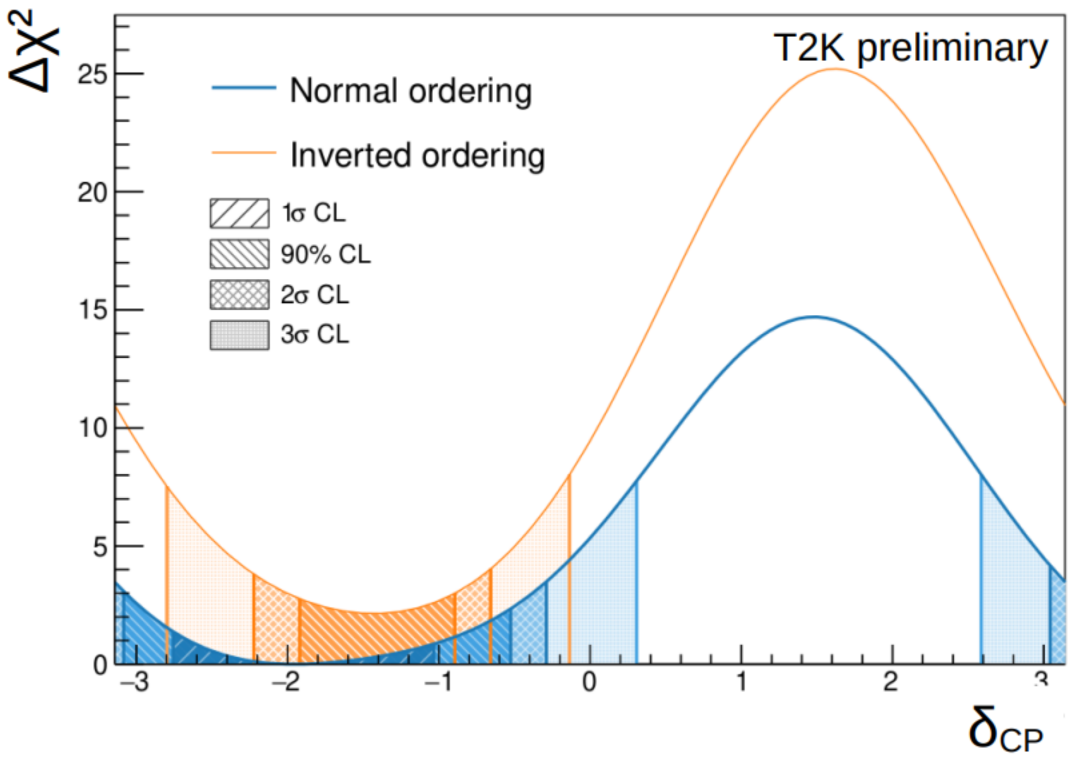


Reactor Constrains Applied

CP phase

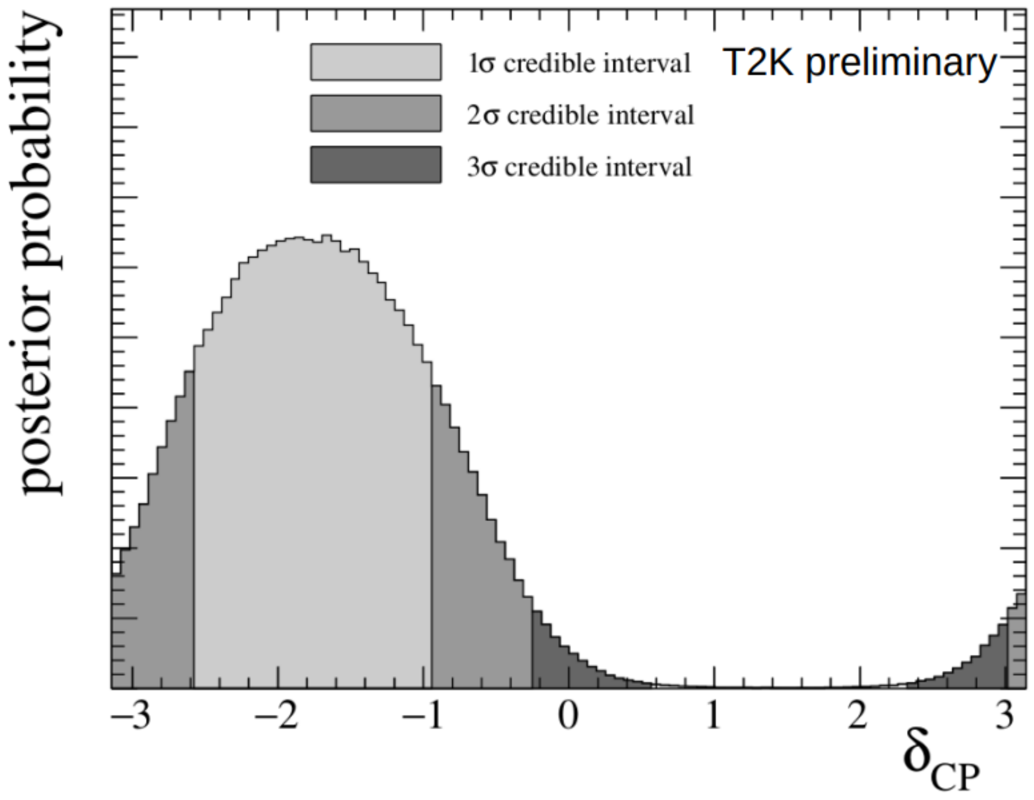
- CP-conserving values of δ_{CP}= 0 and δ_{CP} = π both are outside of 90% CL intervals
- Tested effect of alternative interaction model, did not find biases that would change this conclusion

Frequentist
(Feldman-Cousins method)



Reactor Constrains Applied

Bayesian
(marginalized over MO)



Jarlskog Invariant

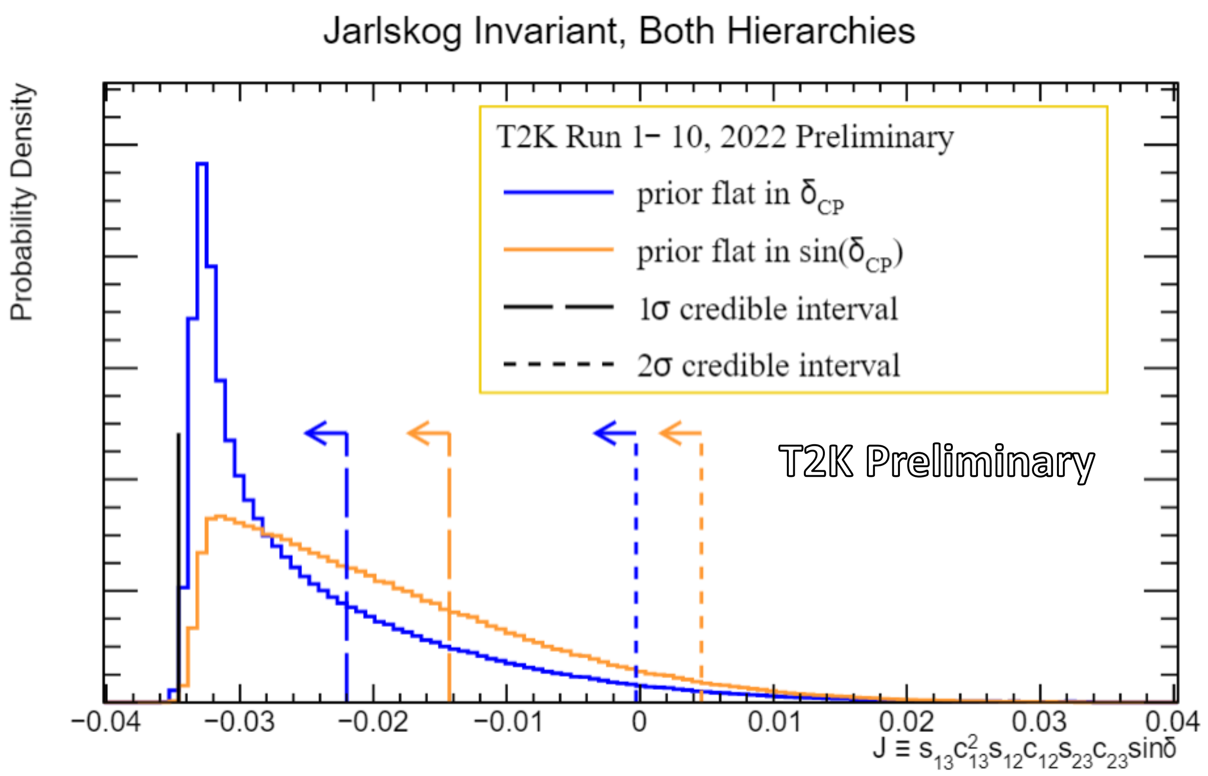
We can perform alternative measurement of CP-violation using Jarlskog invariant.

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

- 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

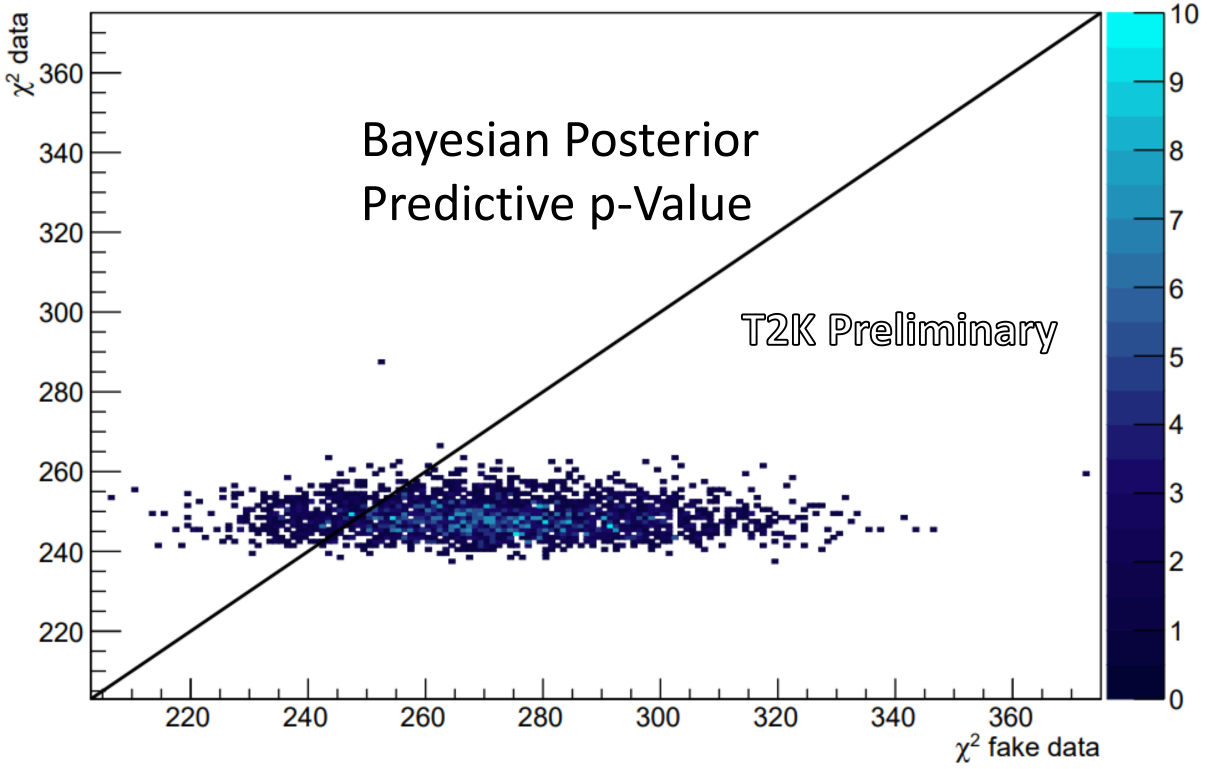


Reactor Constrains Applied

Posterior Predictive p-value

The posterior predictive p-value is meant to answer how likely we are to observe data described by our post-fit model if we were to take the same amount of data again.

This shouldn't be compared to the frequentist p-value which uses prior model.



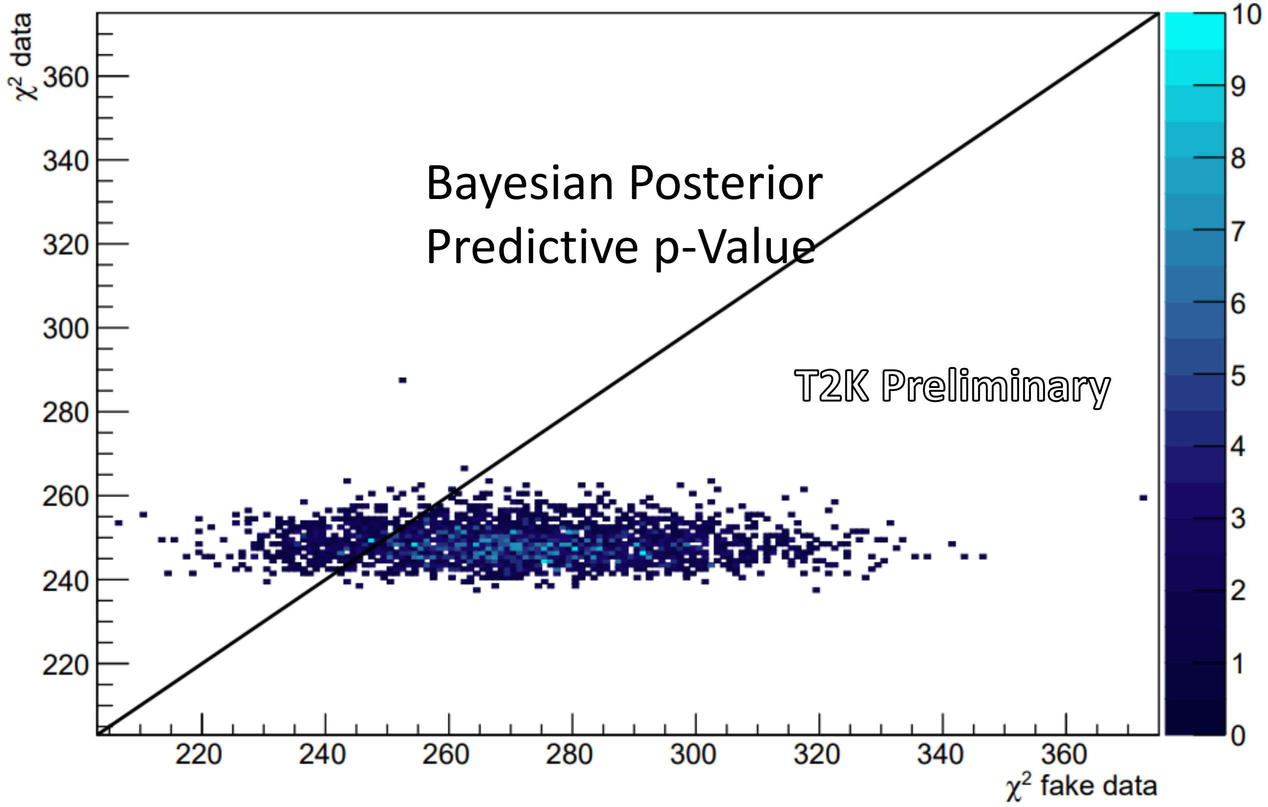
1. A step in the chain is chosen, and the MC is weighted based on that set of parameters
2. The LLH between the real data and the MC is calculated. This is $\boldsymbol{\chi^2 data}$
3. A fluctuated fake data set is created from the weighted MC
4. This data set is treated as 'data' and the LLH between this 'data' and the MC is $\boldsymbol{\chi^2 fake\ data}$

P-Value

$\chi^2 \boldsymbol{data}$ can be naively thought of as a term that shows systematic variation. The systematic part is additionally suppressed by the near-detector constraints.

$\chi^2 \boldsymbol{fake\ data}$ is showing statistical variation.

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

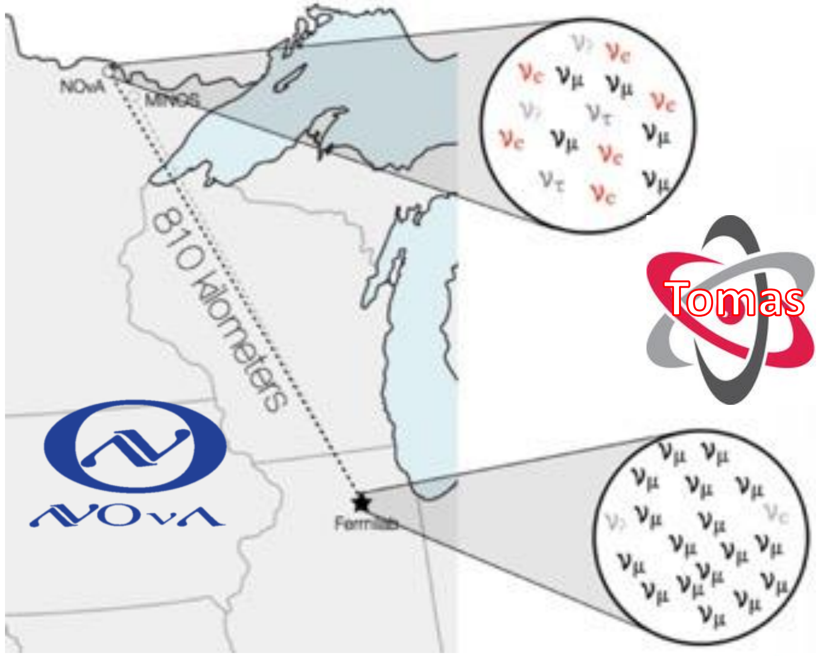


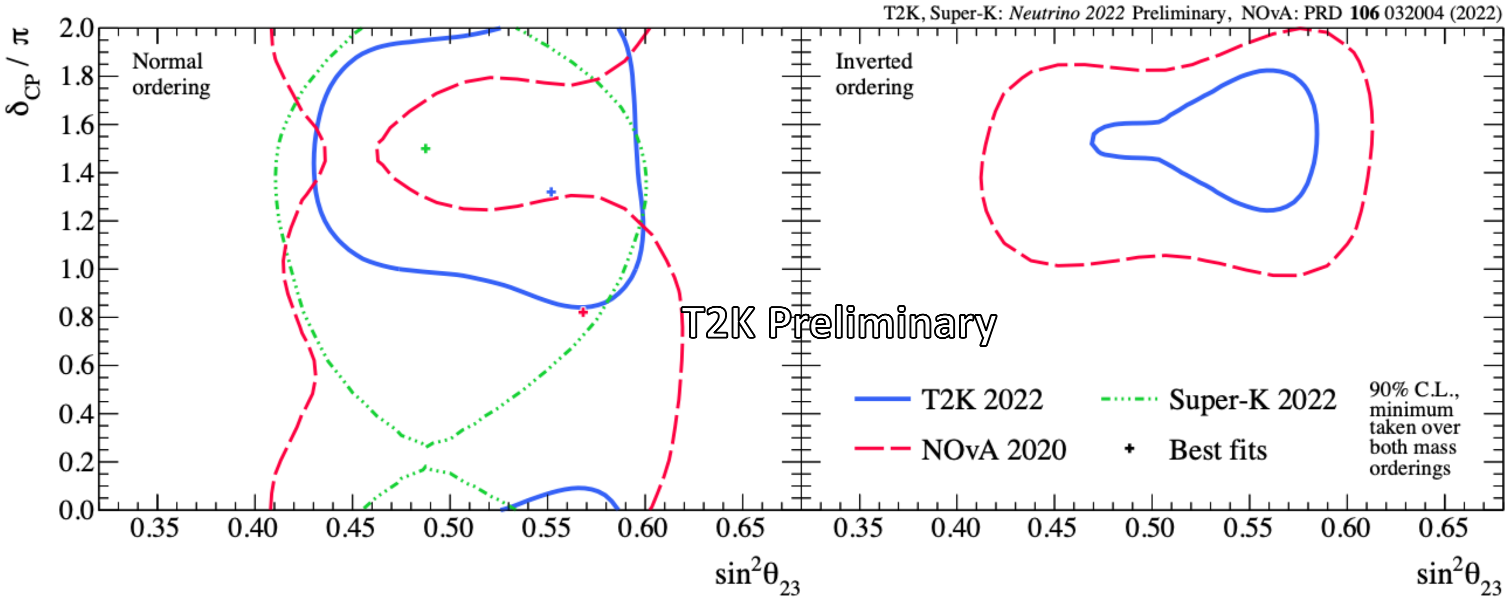

BUT WAIT,
there's more!

T2K-NOvA

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
- Different best fits but no significant tension as overlap that much
- We use different statistical methods even for this overlay — hybrid frequentist vs. frequentist for the overlay. Full joint fit is the way to look at this.





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

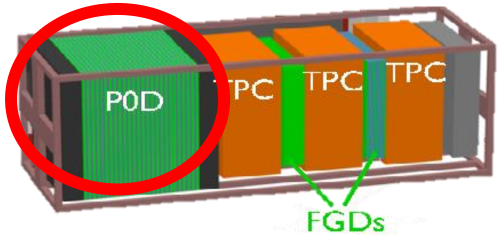
ND280 Upgrade

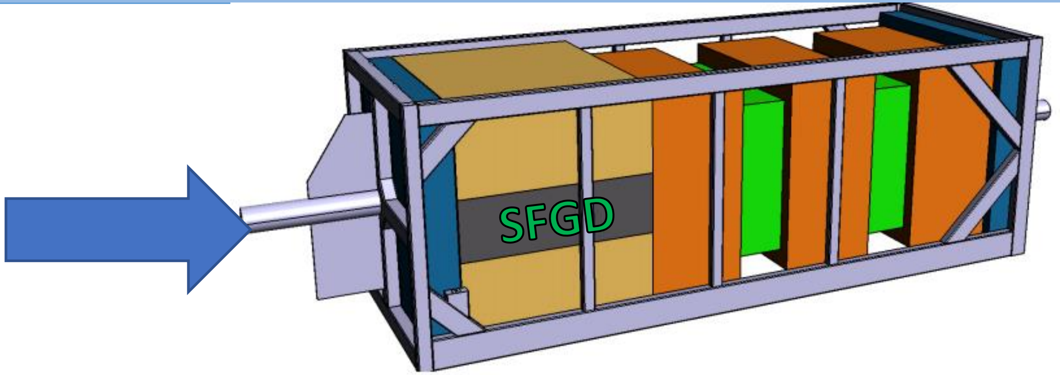
ND280 is currently undergoing upgrade.

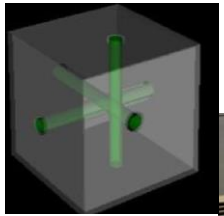
POD is being replaced by new complex with Super-FGD and two HA-TPC

Upgraded detector will have much better angular acceptance.

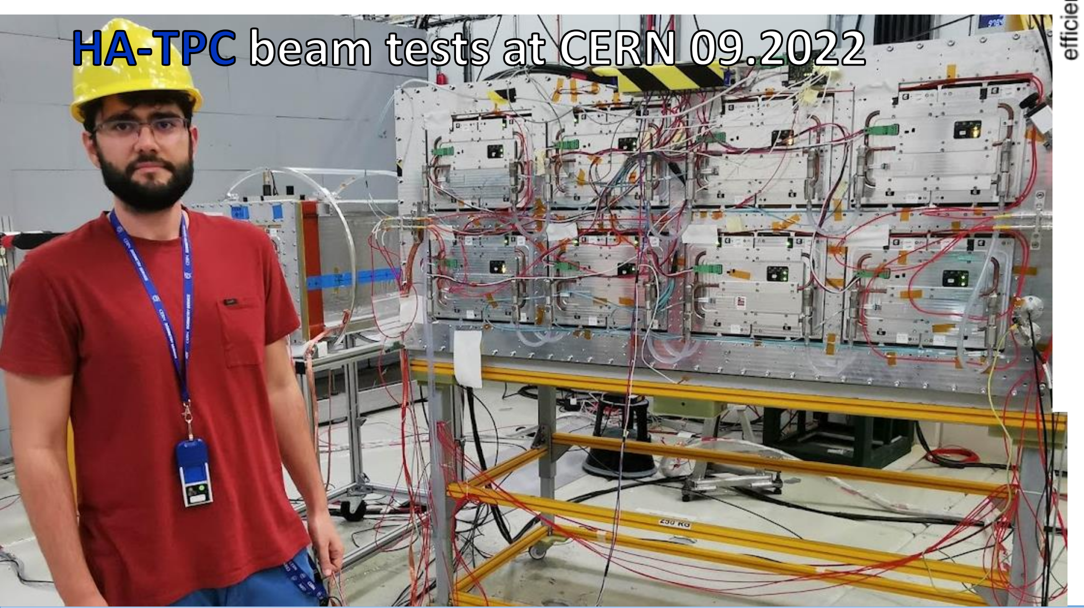
Expected to start taking data in **2023**



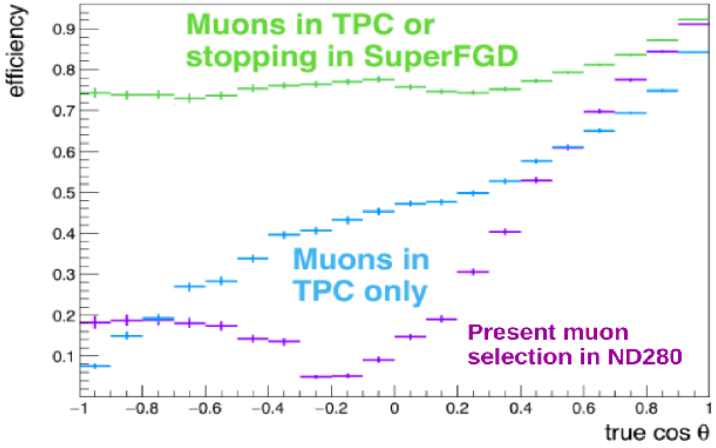


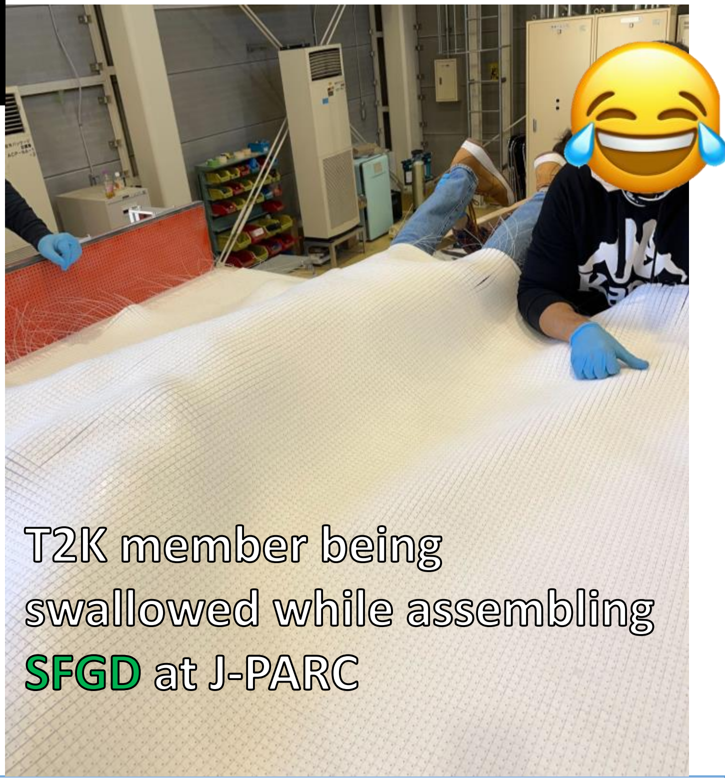


Example of **SFGD** cube



HA-TPC beam tests at CERN 09.2022



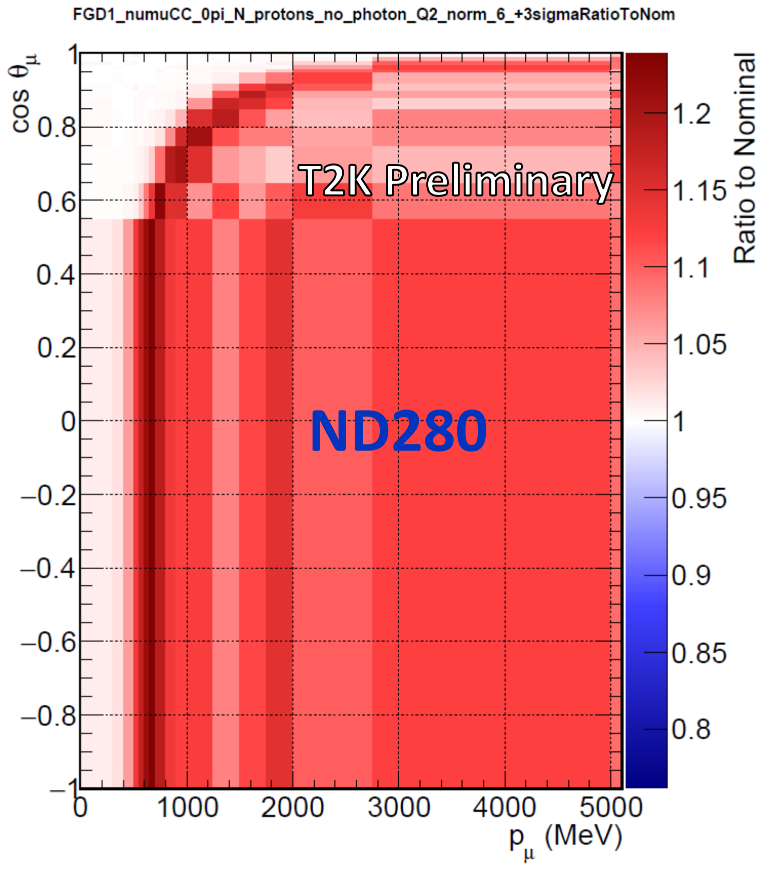


T2K member being swallowed while assembling **SFGD** at J-PARC

Angular Acceptance

Sigma Variation plot:

- Extract distribution at prior values.
- Shift one cross-section parameter by 3σ.
- Make ratio plot of both and see which region is being changed.



ND280 has poor acceptance in the backward region hence binning is very coarse in this region. We only get the general shape.

Angular Acceptance

Sigma Variation plot:

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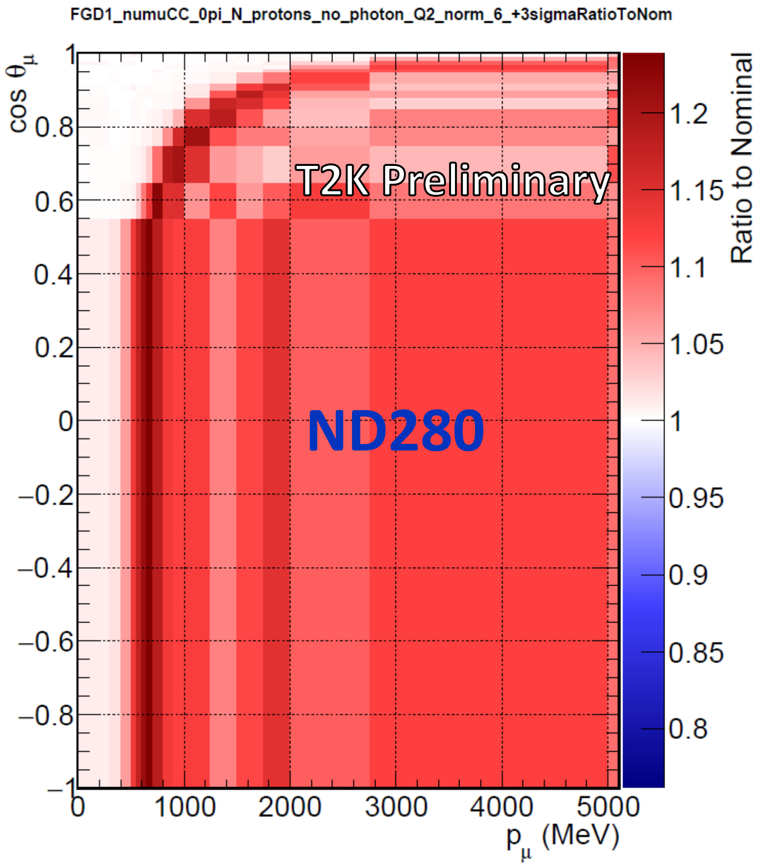
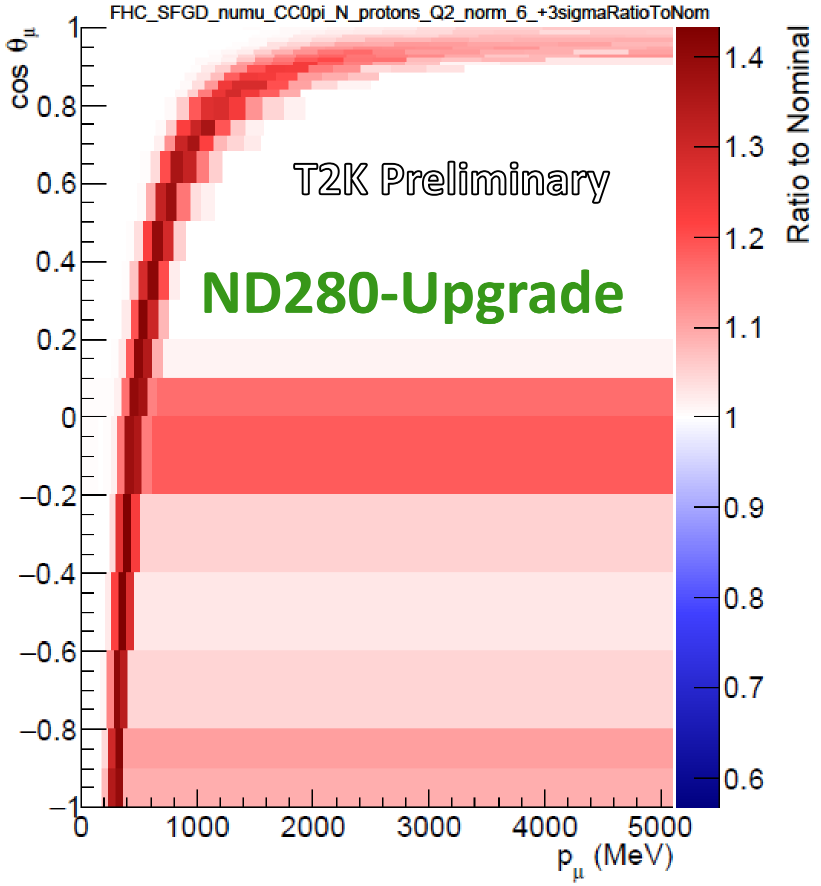


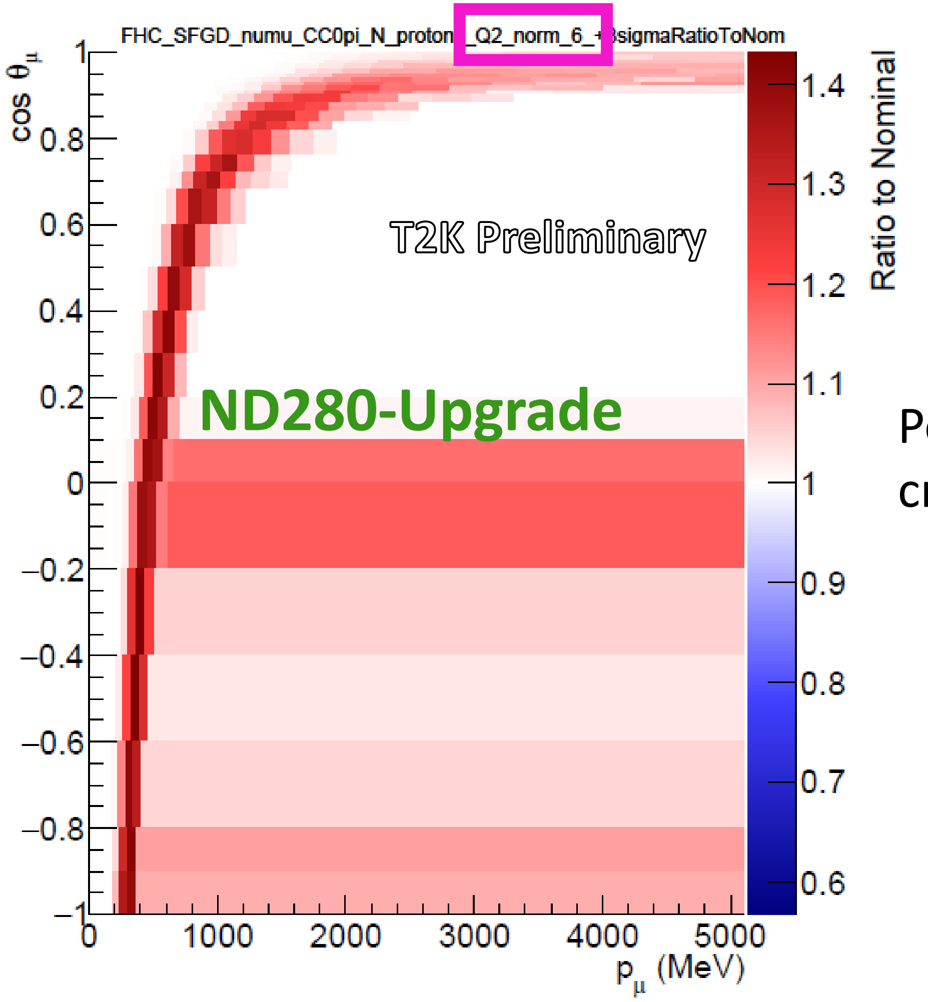
ND280 has poor acceptance in the backward region hence binning is very coarse in this region. We only get the general shape.

ND280-Upgrade, thanks to much better acceptance, can allow for much better binning. Additionally, thanks to the better resolution, we observe much smoother change.

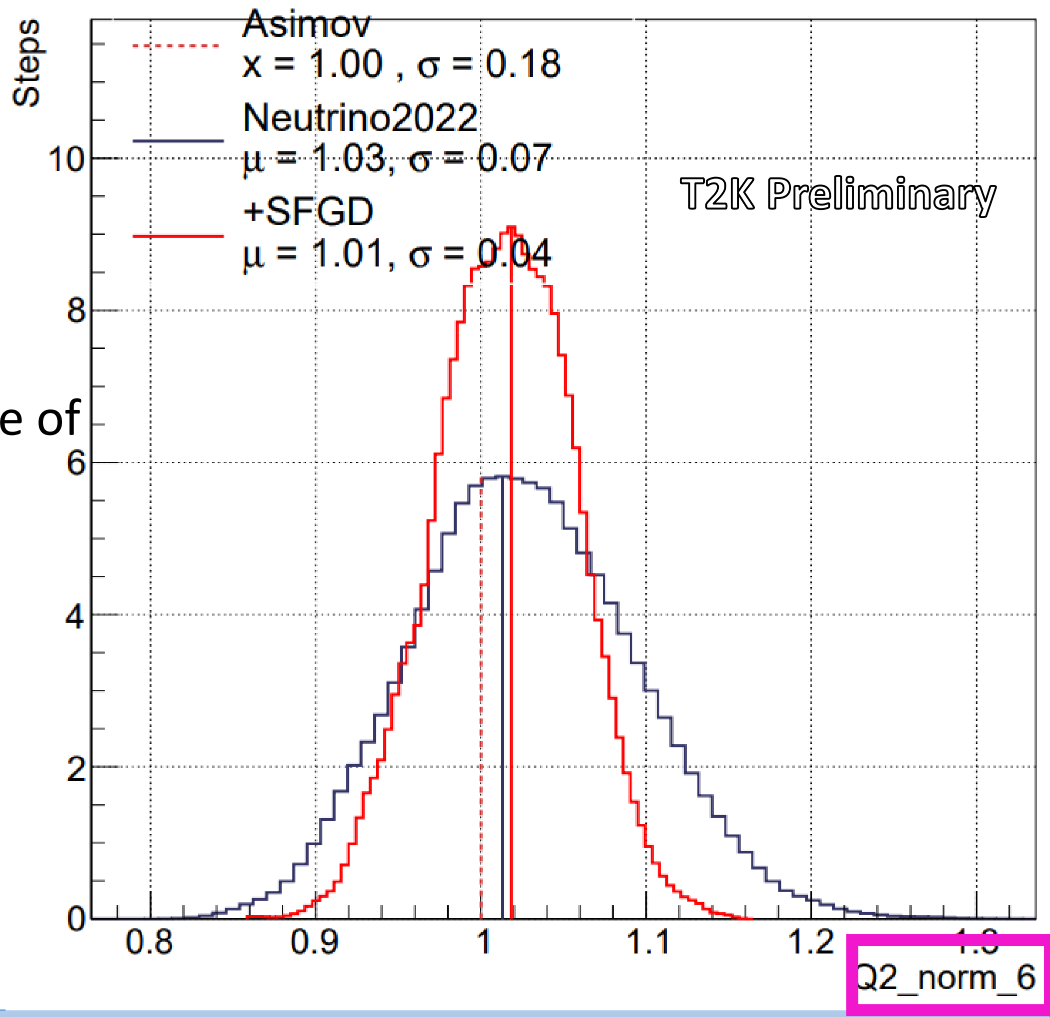


Impact of ND280-Upgrade

With ND280 Upgrade we expect that errors for many cross-section parameters may be reduced even by half.



Posterior distribution for one of cross-section parameters

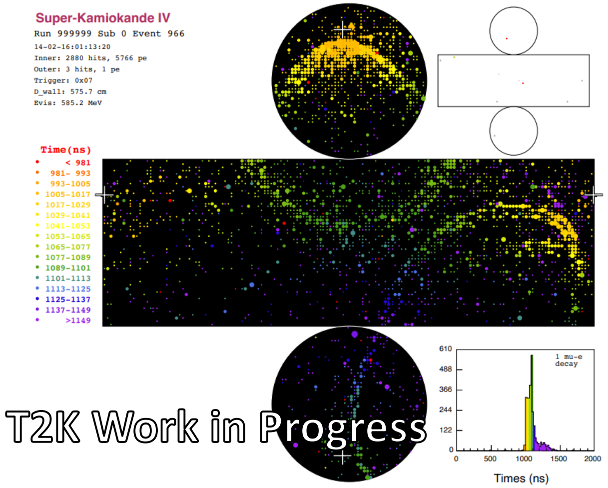


Future Prospects

Improvements to Oscillation Analysis
- Including of Run11 data
- New Multi Ring for ν_e

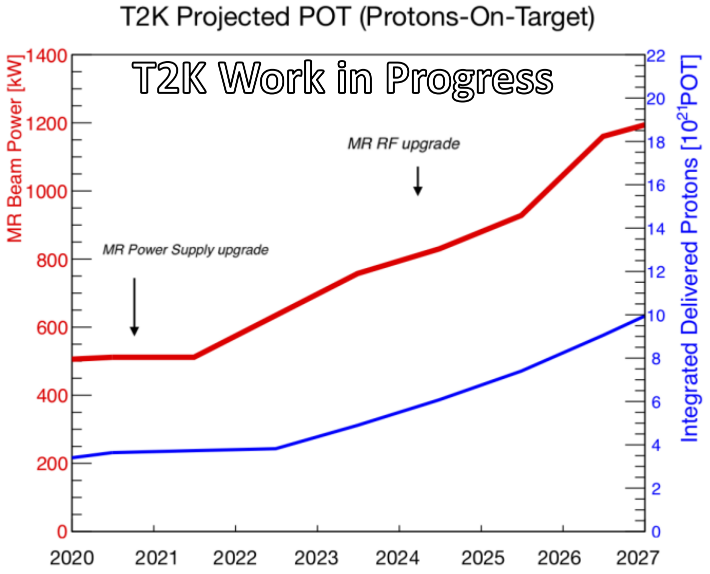
Yashwanth

Maitrayee



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



Summary

Conservation of CP symmetry excluded at the 90% CL level

Mild preference for normal mass ordering and upper θ_{23} 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.

This work is partially supported by the the National Science Centre (UMO-2018/30/E/ST2/00441), and CIS Cluster.

T2K Collaboration

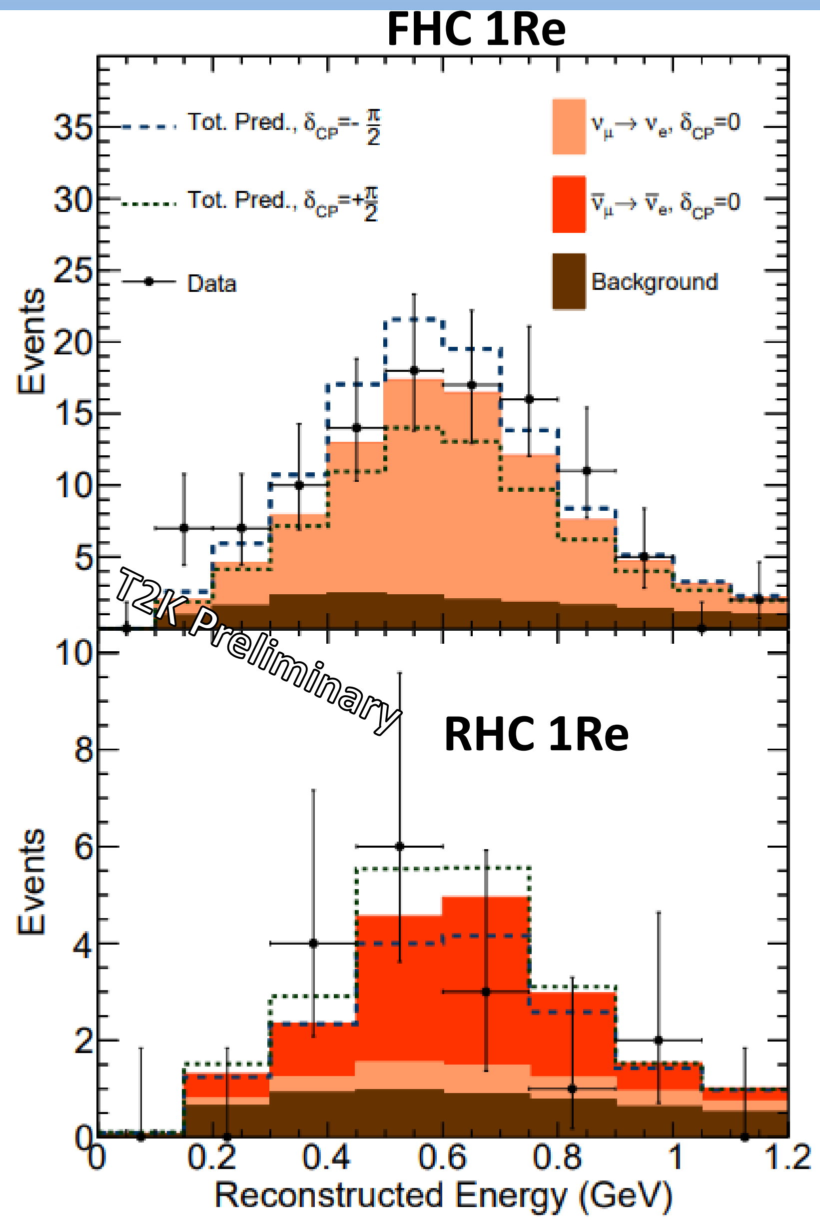
Three flavor collaboration meeting
CERN+J-PARC+Virtual
May 2022

BACKUP

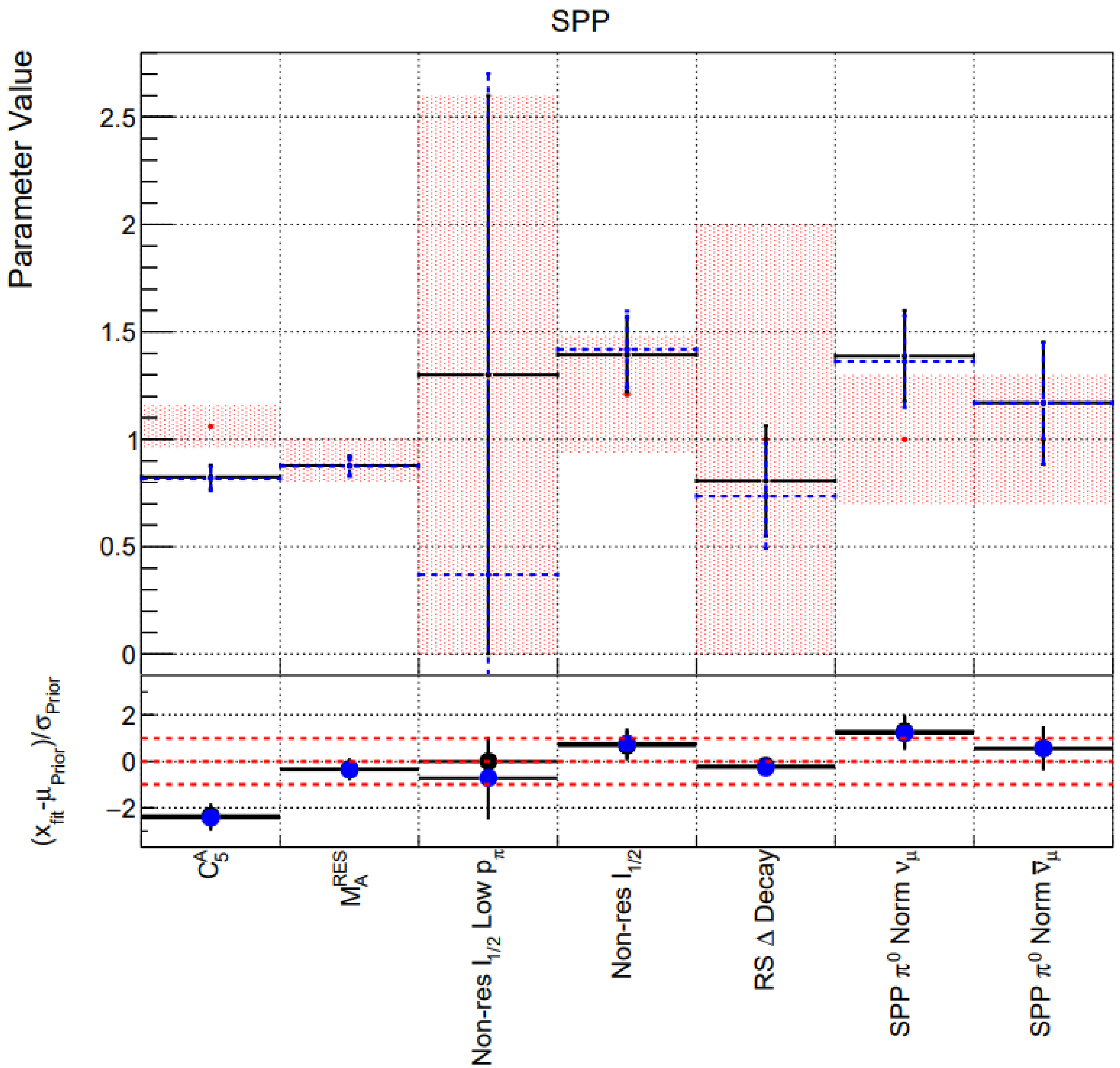
CP Violation

Naively looking at data and MC predictions for both hypothesis we can see by eye that data prefer maximal CP violation.

However, by eye is not a good metric so we did even more tests.



ND vs ND+FD



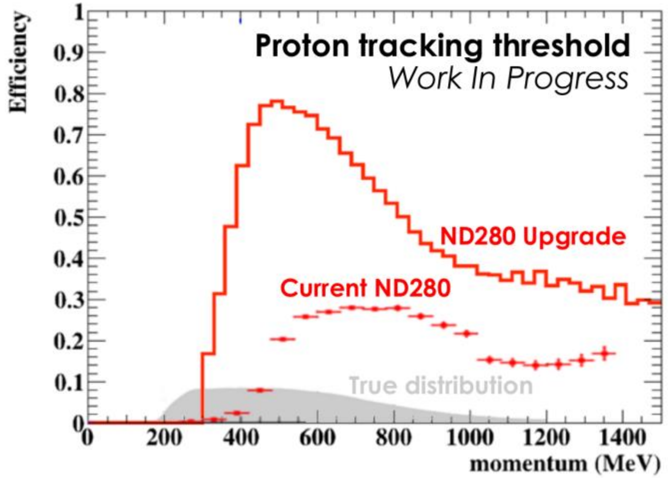
SPP
Parameter Value
2.5
2
1.5
1
0.5
0
$(x_{fit}-\mu_{Prior})/\sigma_{Prior}$
2
0
−2
C_5^A
M_A^{RES}
Non-res $I_{1/2}$ Low p_π
Non-res $I_{1/2}$
RS Δ Decay
SPP π^0 Norm ν_μ
SPP π^0 Norm $\bar{\nu}_\mu$

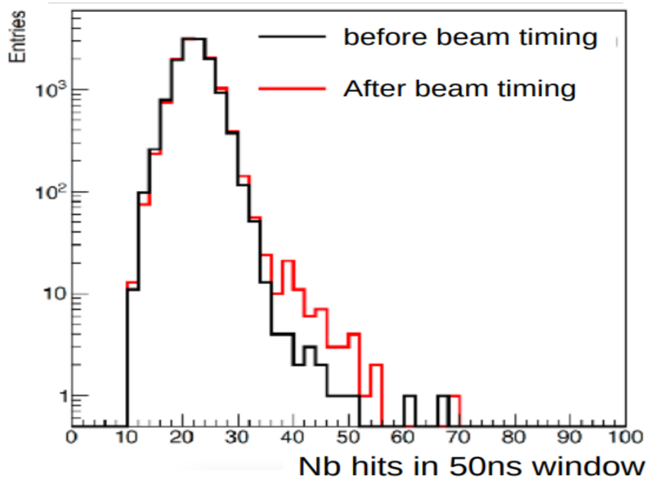
LLH

$$
\begin{aligned}
-\ln\mathcal{L} = & \sum_{i}^{\text{ND280bins}} N_i^{\text{ND,MC}}(\vec{f},\vec{x},d^{\vec{N}D}) - N_i^{\text{ND,data}} + N_i^{\text{ND,data}} \ln\left(\frac{N_i^{\text{ND,data}}}{N_i^{\text{ND,MC}}(\vec{f},\vec{x},d^{\vec{N}D})}\right) + \frac{(\beta_i - 1)^2}{2\sigma_{\beta_i}^2} \\
& + \sum_{i}^{\text{SKbins}} N_i^{\text{SK,MC}}(\vec{f},\vec{x},d^{\vec{S}K}) - N_i^{\text{SK,data}} + N_i^{\text{SK,data}} \ln\left(\frac{N_i^{\text{SK,data}}}{N_i^{\text{SK,MC}}(\vec{f},\vec{x},d^{\vec{S}K})}\right) \\
& + \frac{1}{2}\sum_{i}^{E_\nu bins}\sum_{j}^{E_\nu bins} \Delta\vec{f}_i \left(V_f^{-1}\right)_{i,j} \Delta\vec{f}_j \\
& + \frac{1}{2}\sum_{i}^{\text{xsecpars}}\sum_{j}^{\text{xsecpars}} \Delta\vec{x}_i \left(V_x^{-1}\right)_{i,j} \Delta\vec{x}_j \\
& + \frac{1}{2}\sum_{i}^{\text{ND280det}}\sum_{j}^{\text{ND280det}} \Delta d^{\vec{N}D}{}_i \left(V_{d^{ND}}^{-1}\right)_{i,j} \Delta d^{\vec{N}D}{}_j \\
& + \frac{1}{2}\sum_{i}^{\text{SKdet}}\sum_{j}^{\text{SKdet}} \Delta d^{\vec{S}K}{}_i \left(V_{d^{SK}}^{-1}\right)_{i,j} \Delta d^{\vec{S}K}{}_j \\
& + \frac{1}{2}\sum_{i}^{\text{oscpars}}\sum_{j}^{\text{oscpars}} \Delta\vec{o}_i \left(V_o^{-1}\right)_{i,j} \Delta\vec{o}_j
\end{aligned}
\tag{5.13}
$$

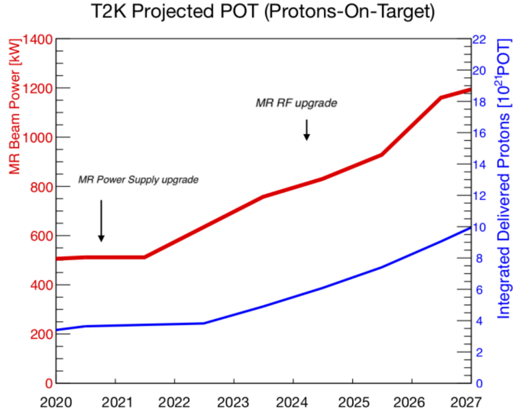
T2K Upgrades

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



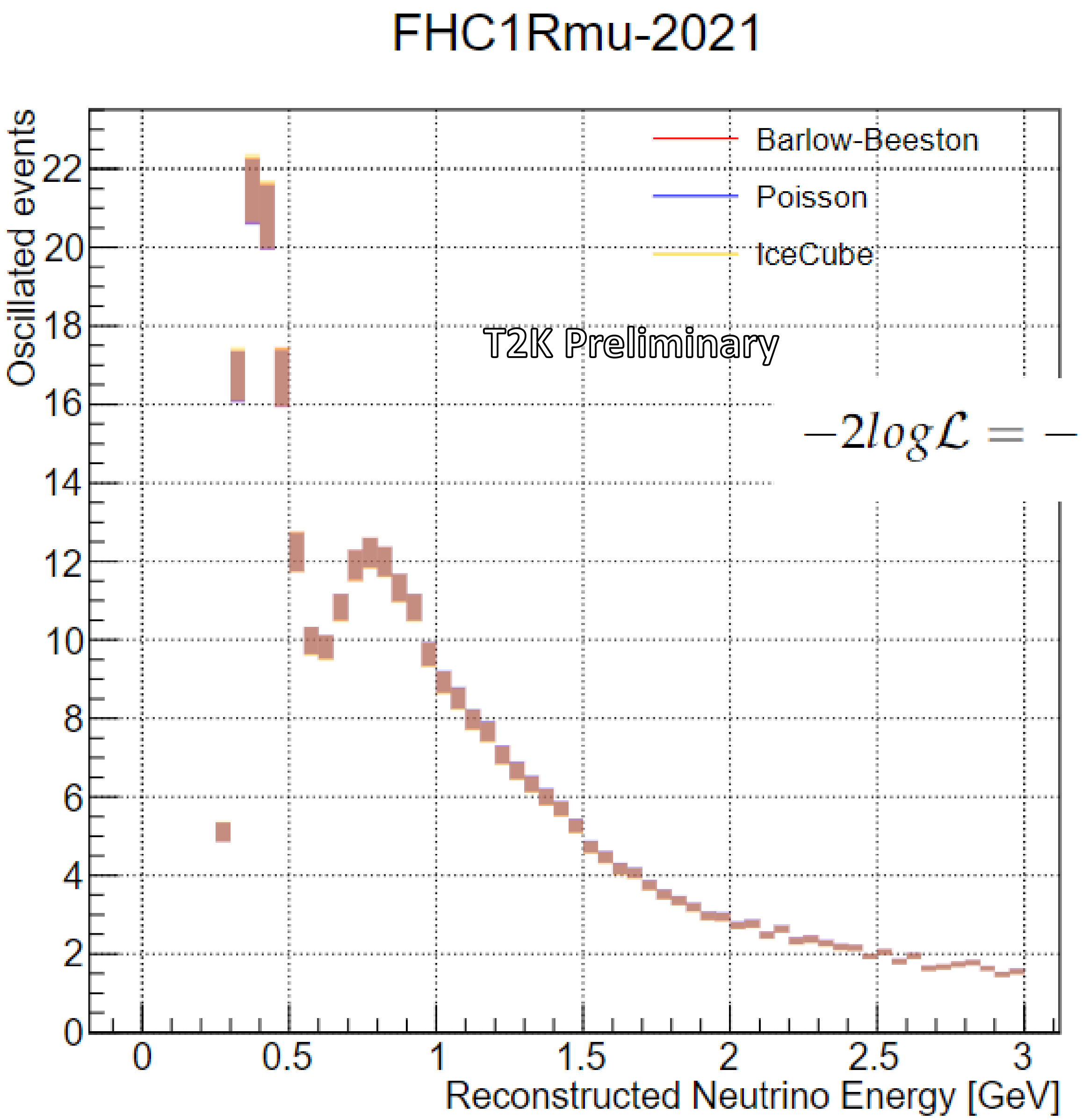


SK-GD
- Super-K was loaded with Gadolinium sulfate, giving improved neutron tagging ability (summer of 2020)
- T2K already recorded data (“Run 11”) during this SK-Gd phase, not yet used in analysis
- Second phase of Gd loading started in May



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

Introduction



Poisson

$$\Delta\chi^2 = -2\log\mathcal{L}_{\mathrm{Stat}} = 2\sum_i\left[N_i^{\mathrm{MC}}(\vec{\theta}) - N_i^{\mathrm{data}} + N_i^{\mathrm{data}}\ln\left(\frac{N_i^{\mathrm{data}}}{N_i^{\mathrm{MC}}(\vec{\theta})}\right)\right]$$

Barlow-Beeston

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

Ice-Cube

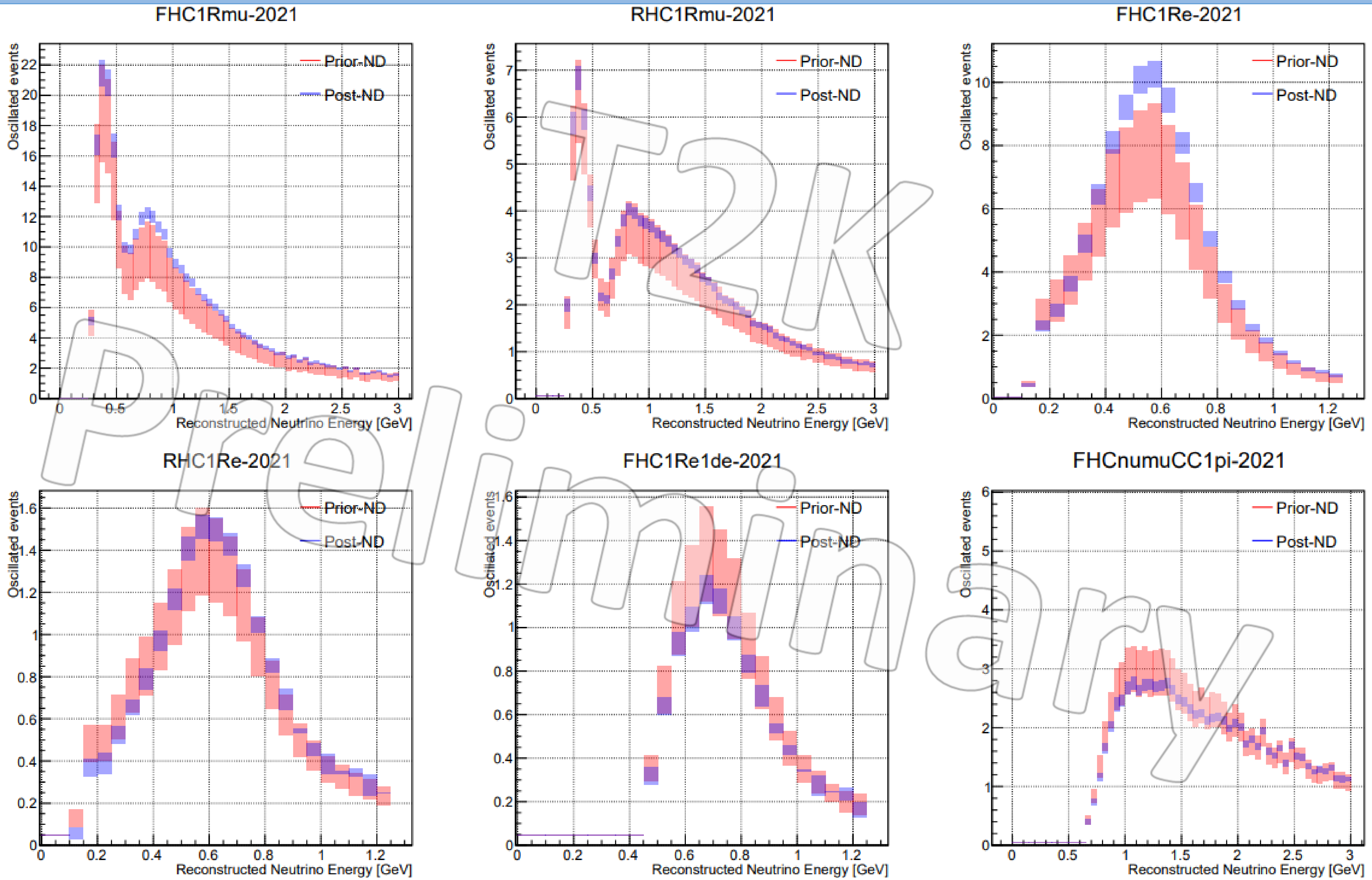
$$-2log\mathcal{L} = -\left(a\log(b) + \log[\Gamma(k+a)] - (k+a)\log(b+1) - \log[\Gamma(a)]\right)$$

In the main fit we use Barlow-Beeston however we checked that choice of LLH doesn't change results.

There is another LLH that we don't use at all.

I know Clarence did some checks but couldn't find all information, so I did check on my own.

FD spectra before/after ND



Questions in Neutrino Oscillation Physics

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

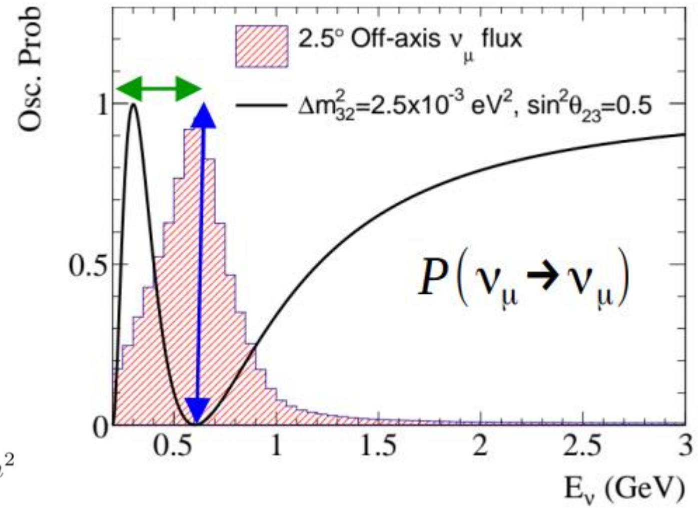
Appearance channel

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

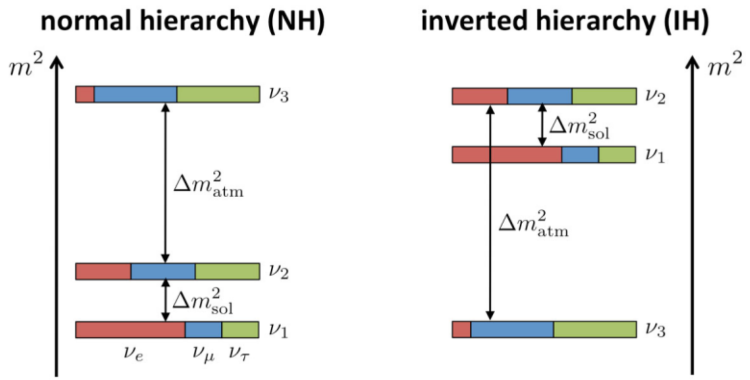
Jarlskog Invariant $J_{CP} \approx 0.033\sin(\delta_{CP})$

- Octant of θ_{23}

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



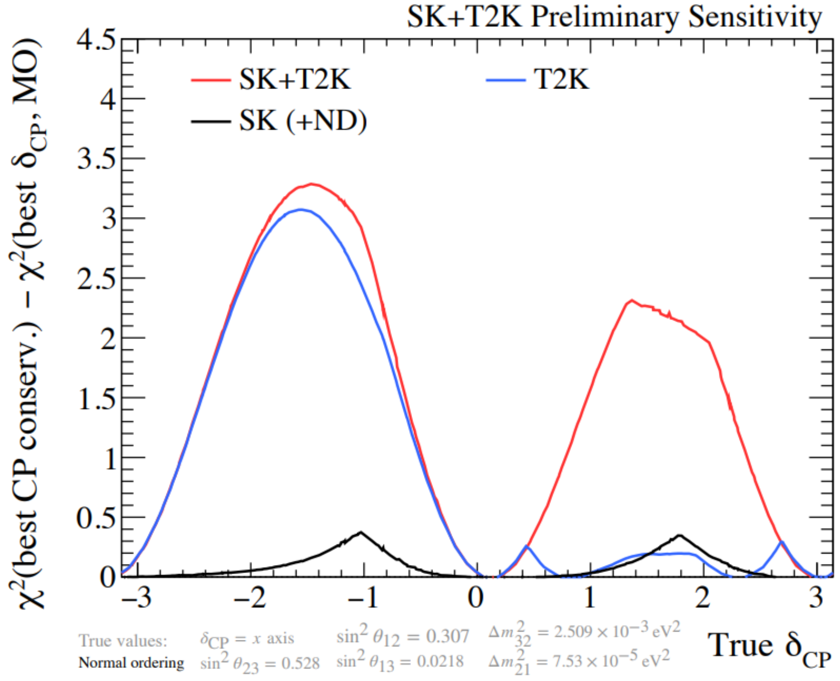
- Mass ordering



Joint Fits

T2K-SK atmospheric joint analysis

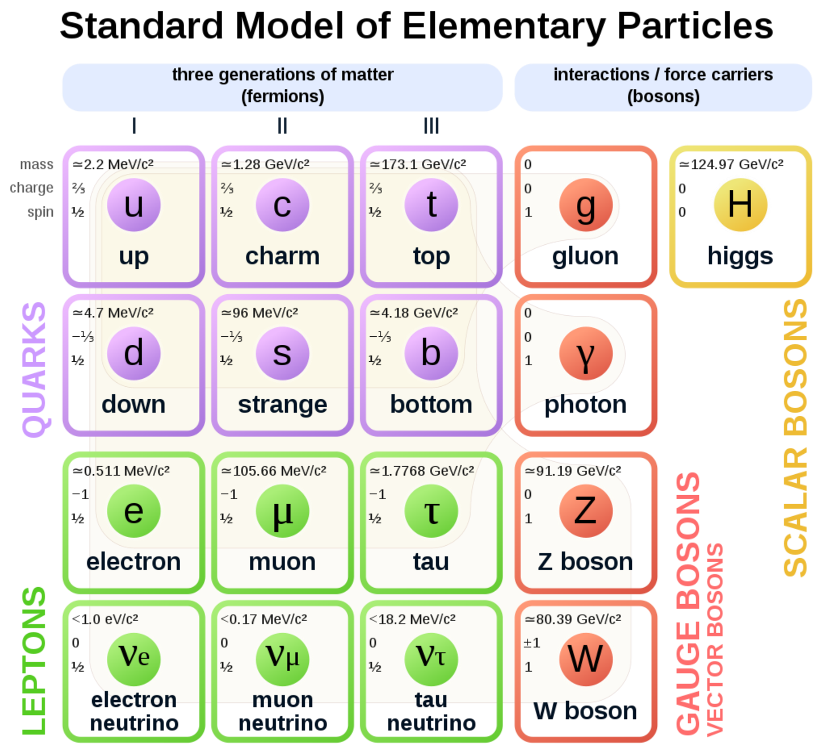
- Common detector between two experiments: need to check effect of correlations between systematics
- Super-K atmospheric samples cover wider range of energies and baseline than T2K, with in particular sensitivity to **MO** from high energy neutrinos
- Performed sensitivity studies for the common analysis

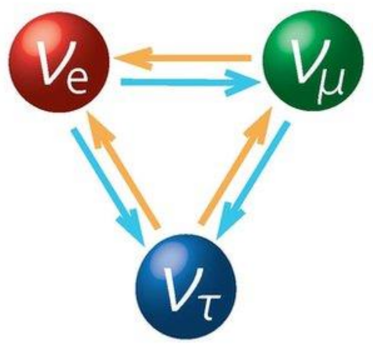


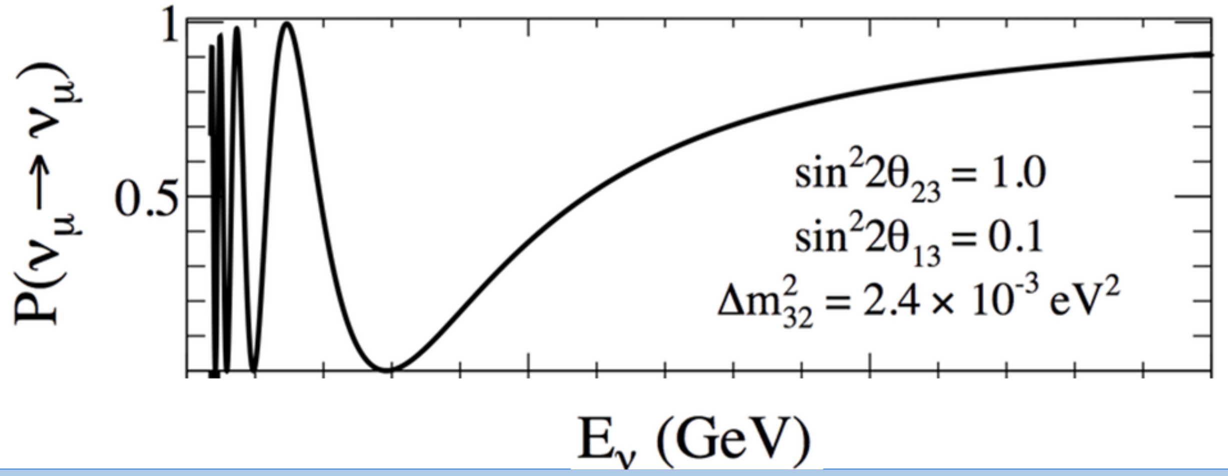
Neutrino Introduction

Neutrino are elementary lepton particles.

One key feature of neutrino **are oscillations.** Neutrinos while propagating through time and space can change flavor.







Systematic uncertainties FD

Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	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

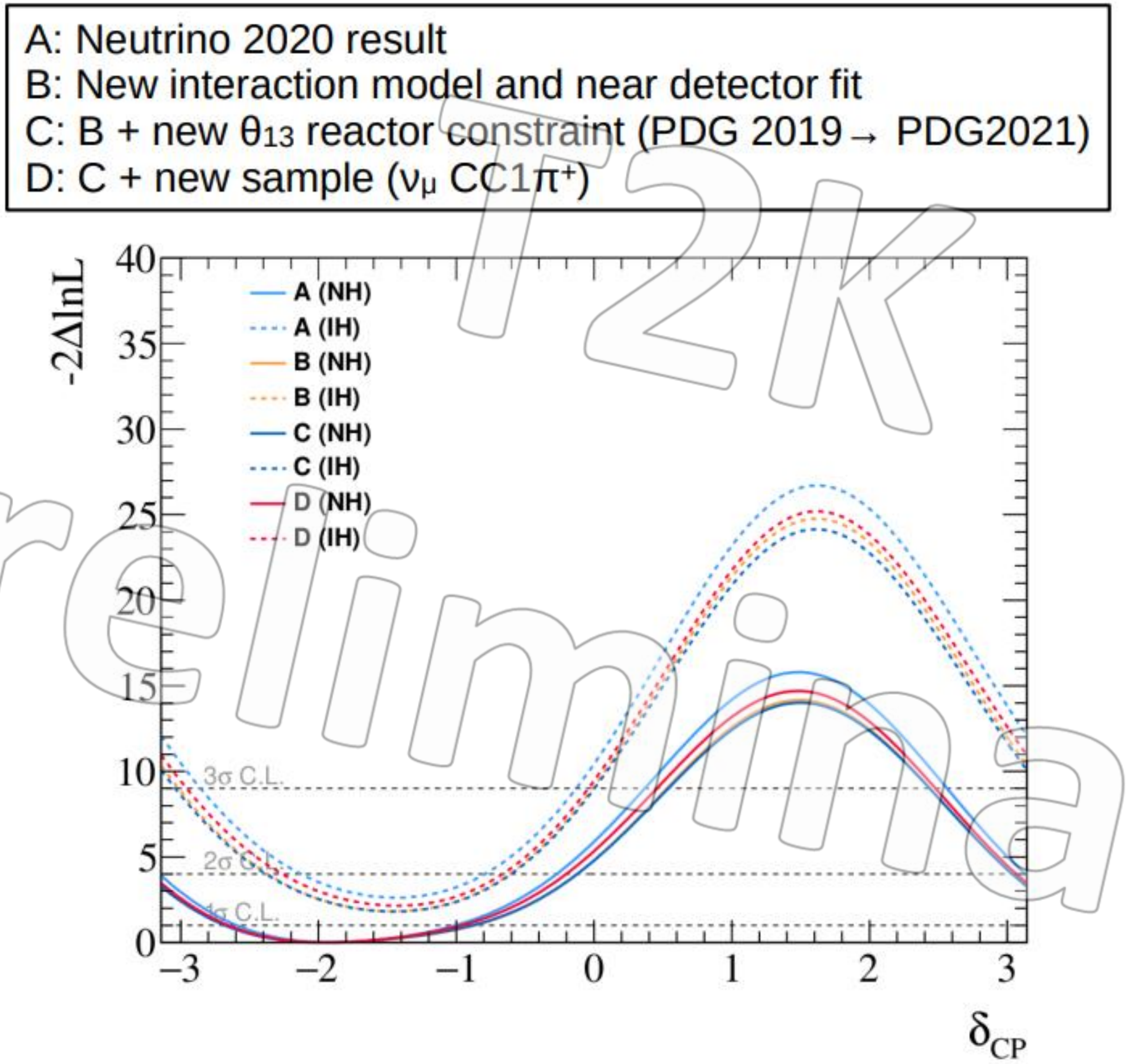
Note:

- 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

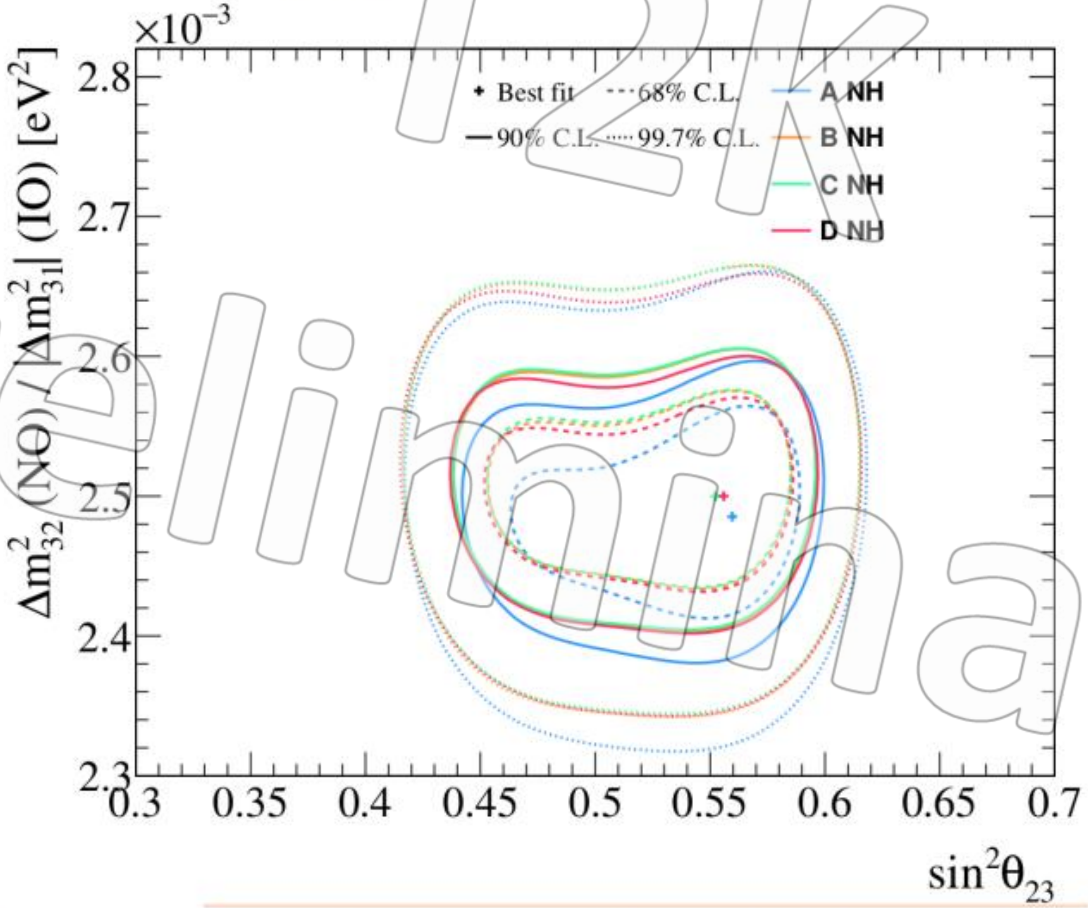
Effect of Analysis Change



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

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: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

Effect of Analysis Change

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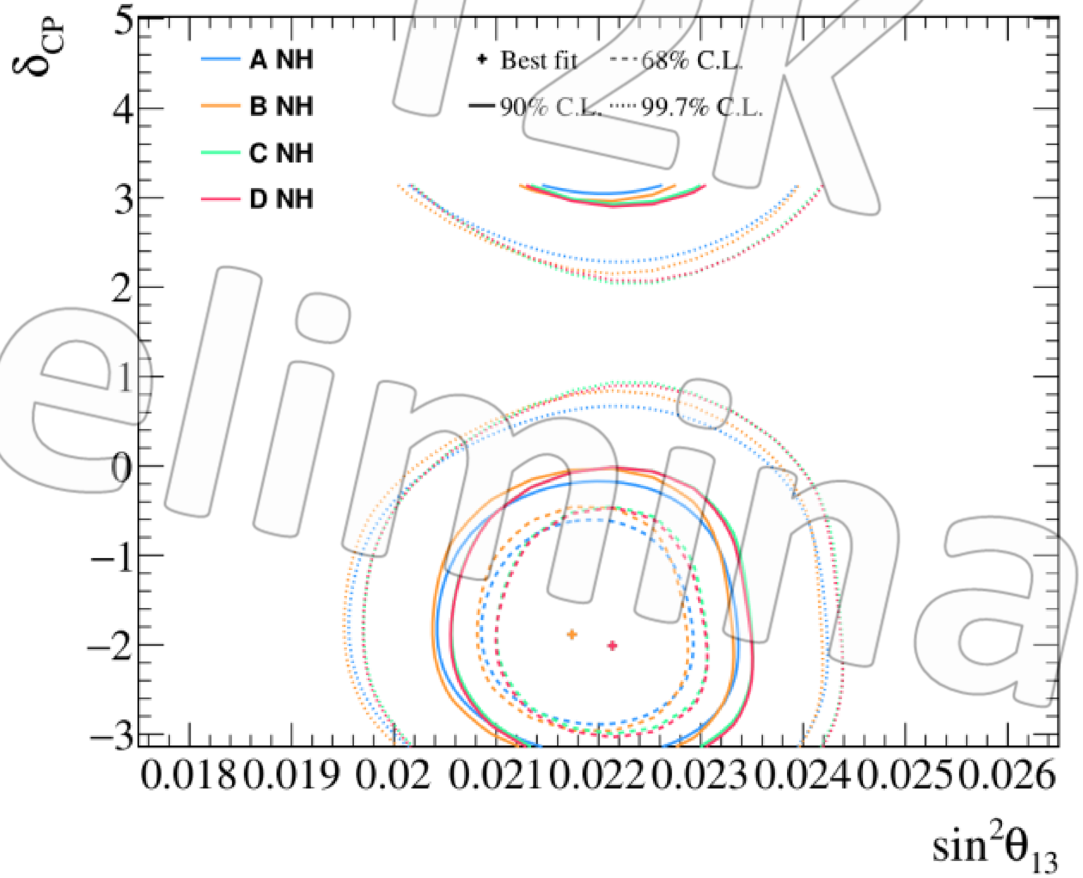
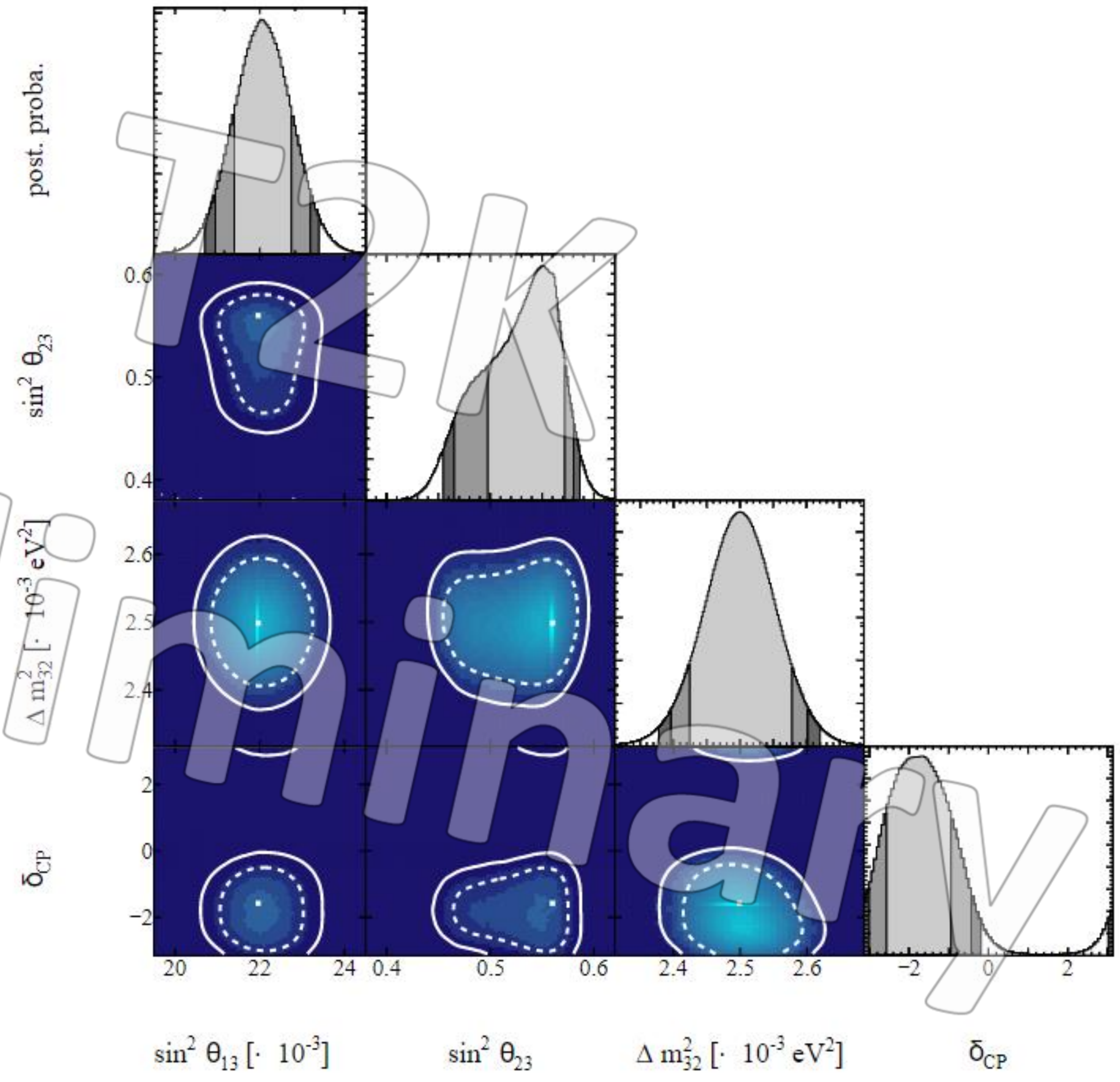
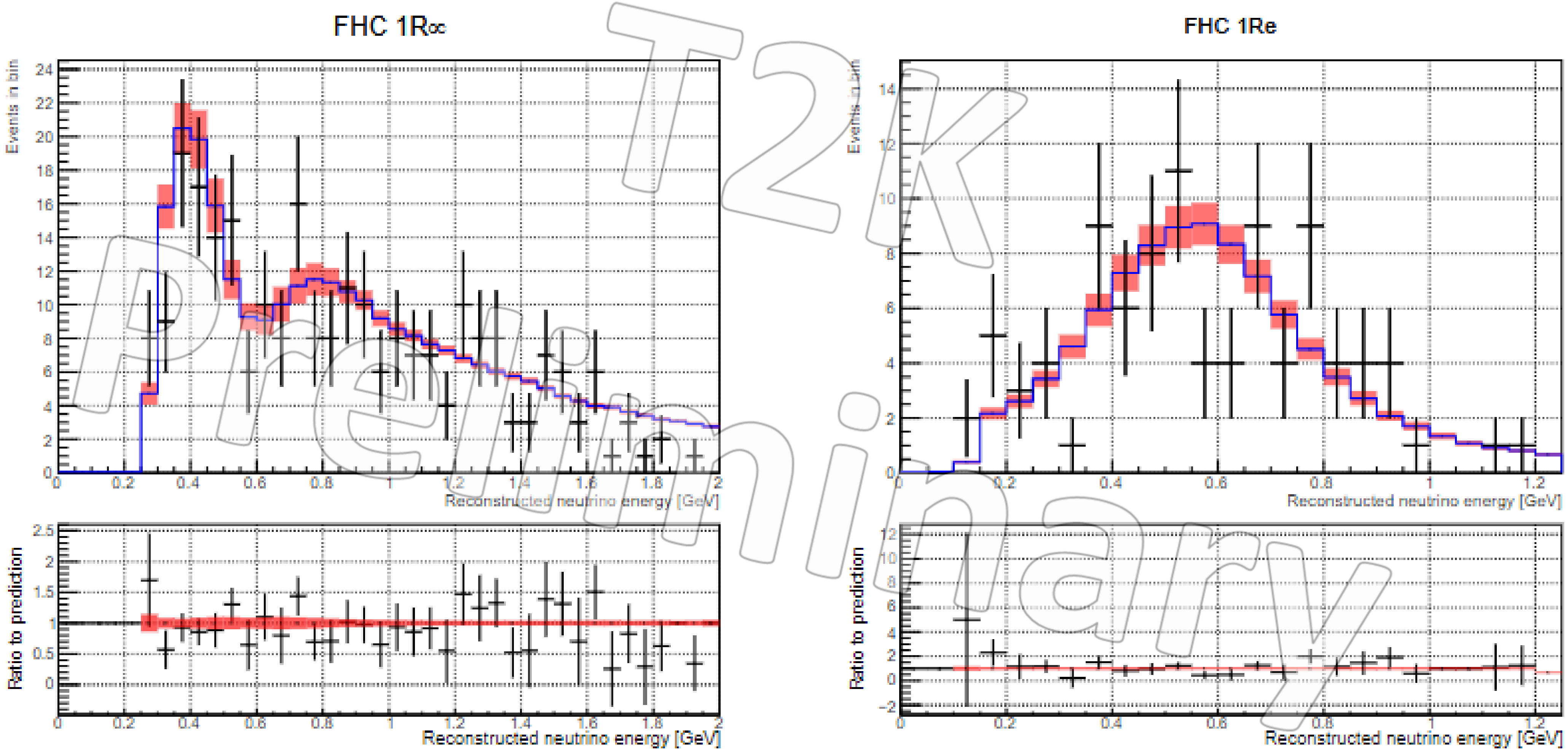


Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

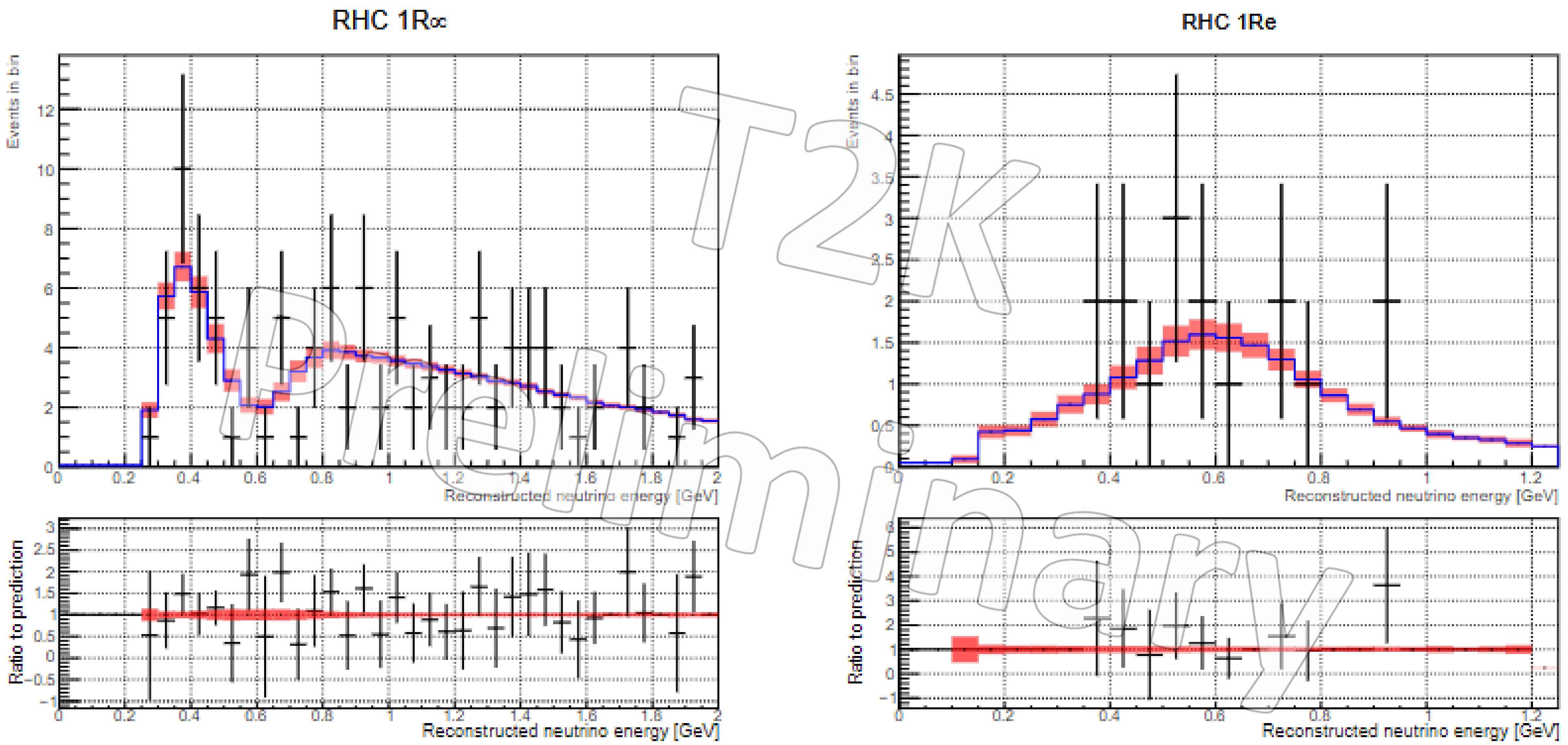
Triangle Plot



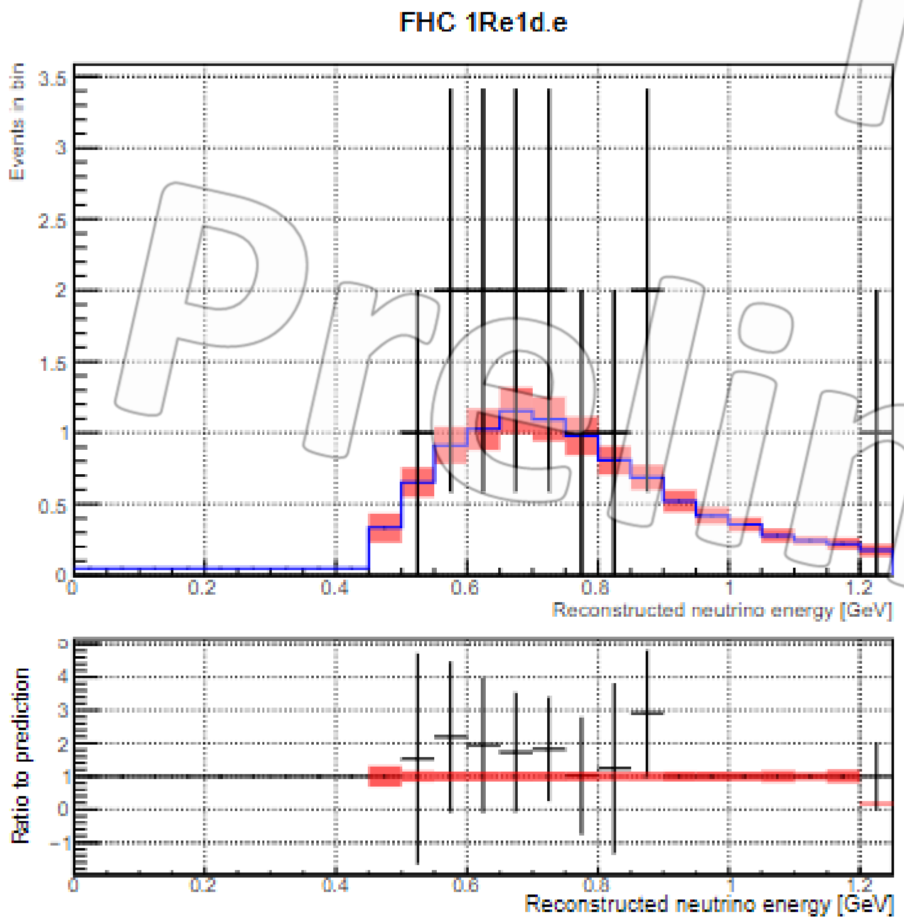
Posterior Predicive

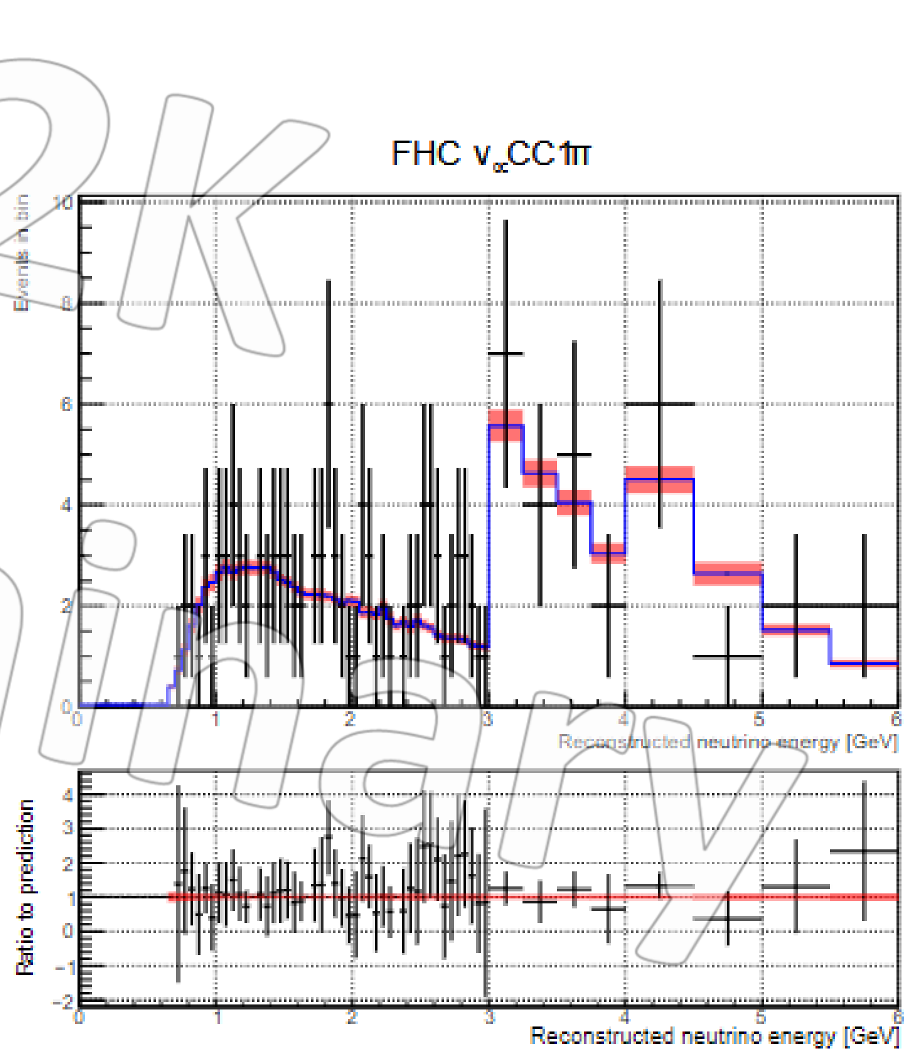


Posterior Predicive

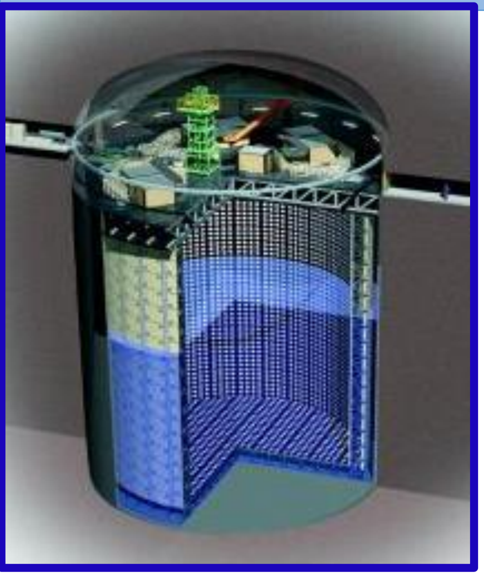


Posterior Predicive

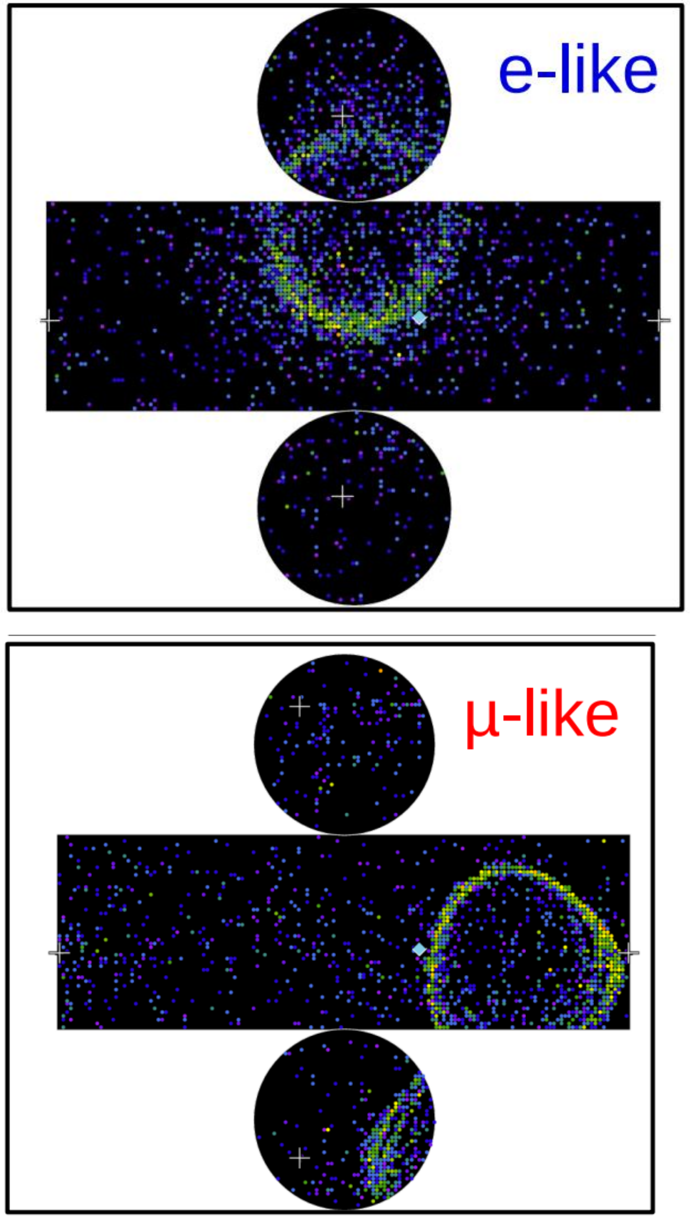


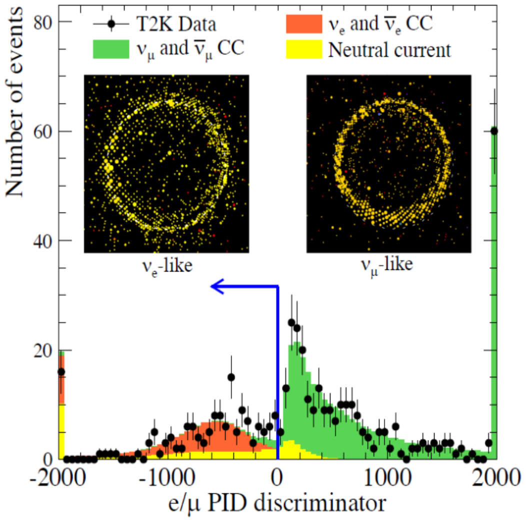


Far Detector Sample



- 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