Newest T2K results on neutrino oscillations

and NCBJ coup d'état

Kamil Skwarczyński

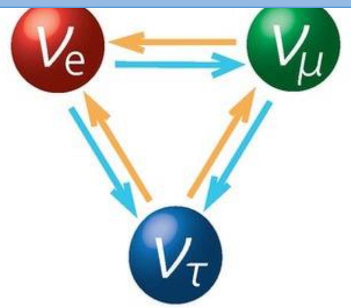
On behalf of NCBJ neutrino group

16.12.2022

NATIONAL CENTRE FOR NUCLEAR RESEARCH
ŚWIERK

T2K

CP Violation in Lepton Sector



Neutrinos can change the flavour while travelling, 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

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

CP violation in lepton sector means that neutrino oscillation probabilities are different than for antineutrino. The parameter describing CP violation is $\boldsymbol{\delta_{CP}}$.

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

Jarlskog Invariant in general

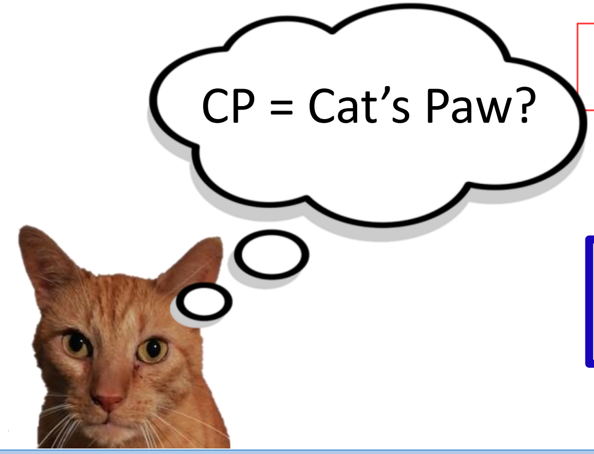
$$J = \frac{1}{8} \operatorname{Im}\left[U_{23} U_{12} U^*_{22} U^*_{13}\right]$$

Jarlskog Invariant In lepton sector

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

Jarlskog Invariant In quark sector

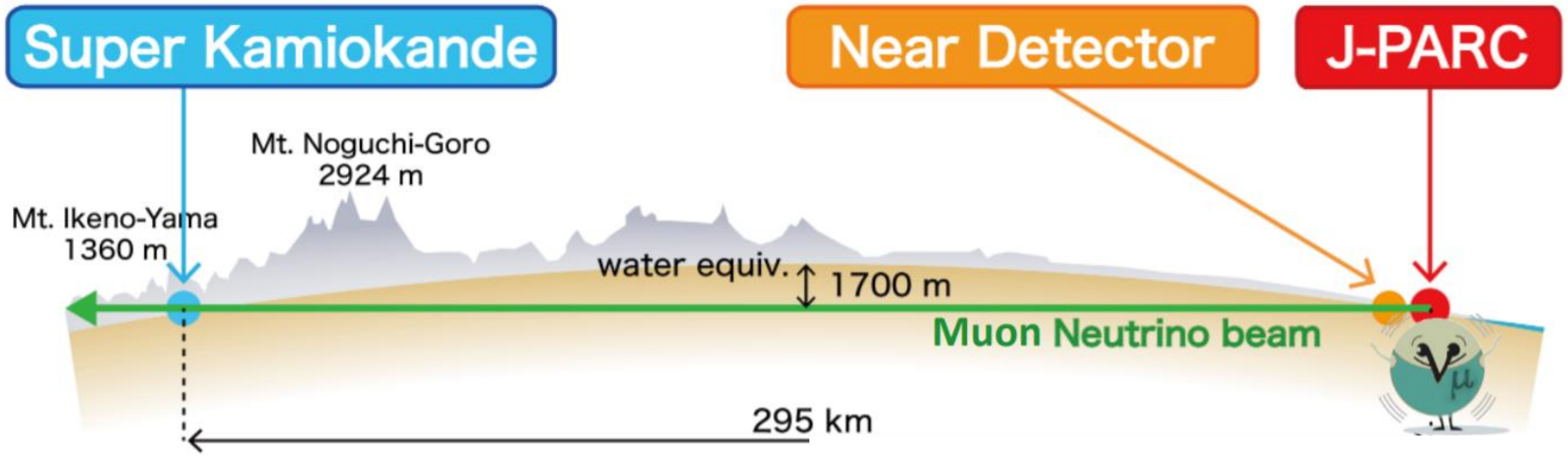
$$J_{CP,q} = 3 \times 10^{-5}$$

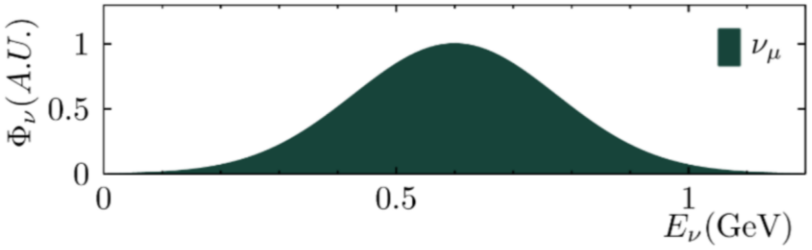


T2K Experiment

T2K is located in Japan

- We create (mostly) muon neutrinos at J-PARC.
  - For neutrino beam modeling we use **NA61/SHINE** data constraints.





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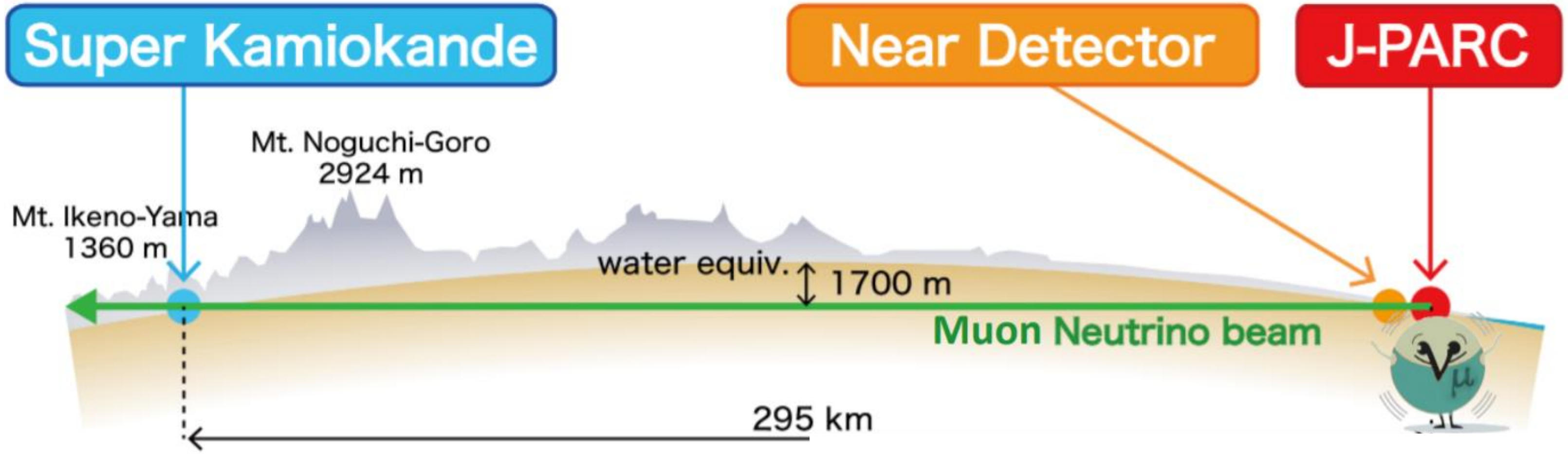

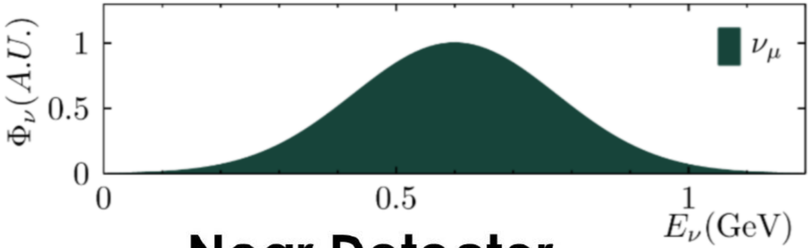

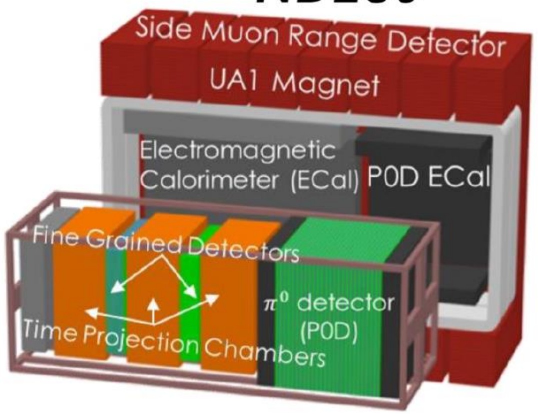

T2K Experiment

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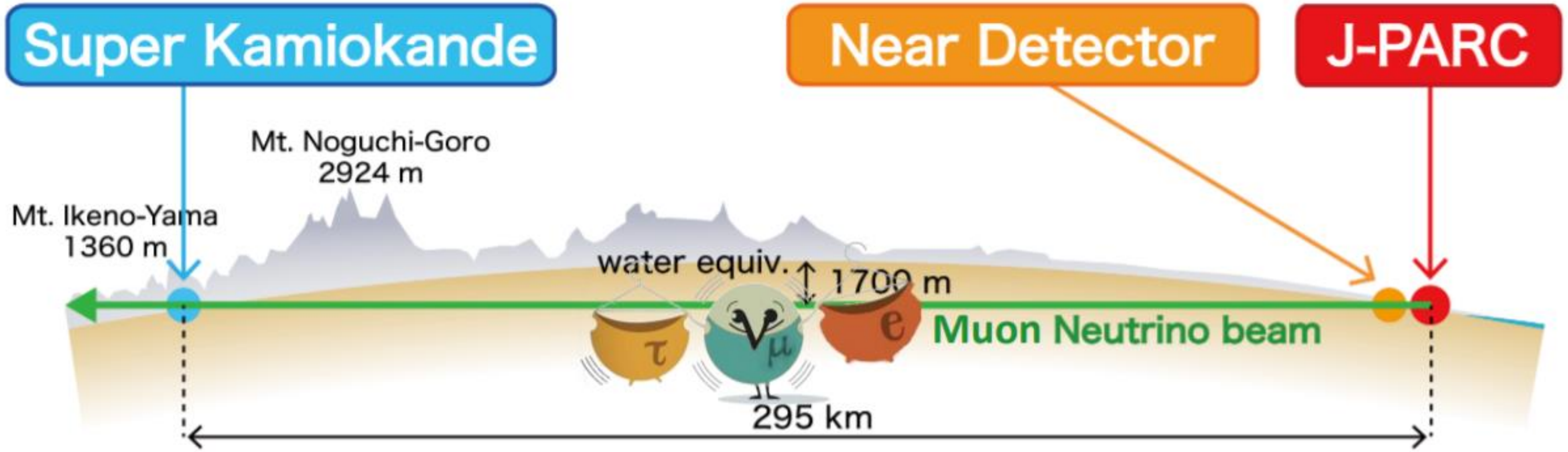
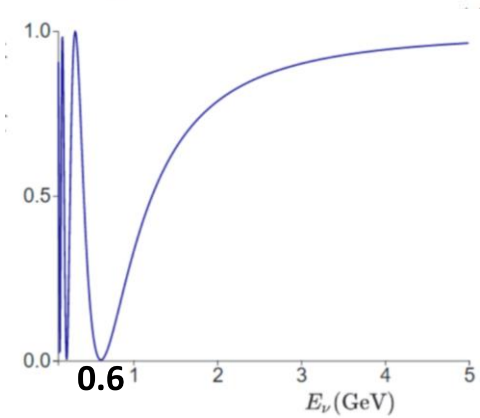
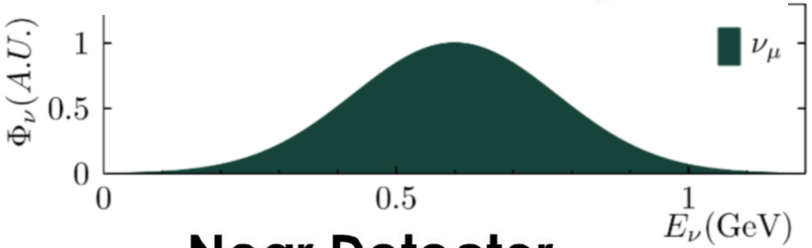
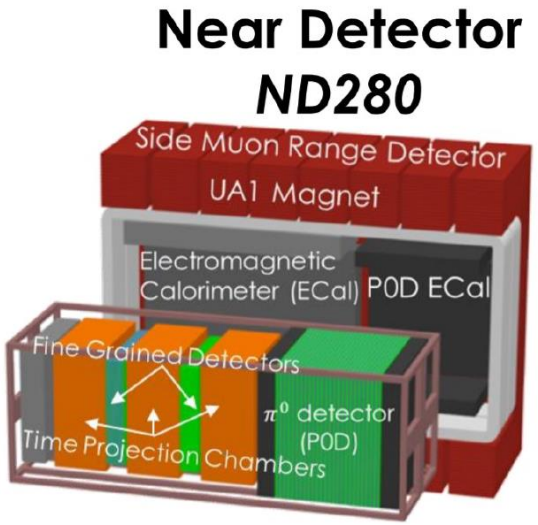
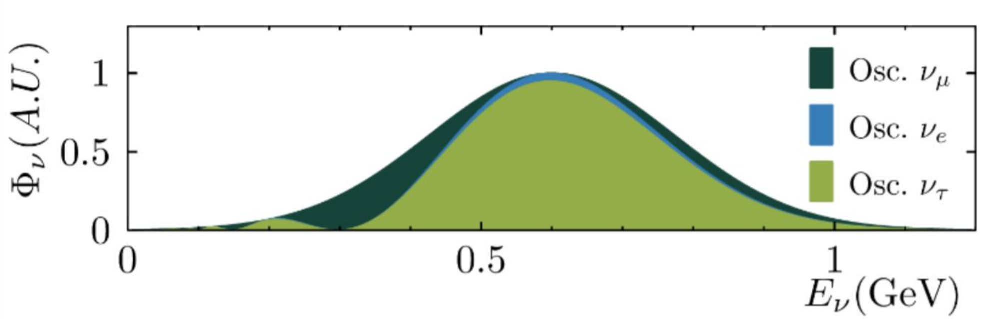
- We measure neutrinos with Near Detector.
- Neutrinos oscillate







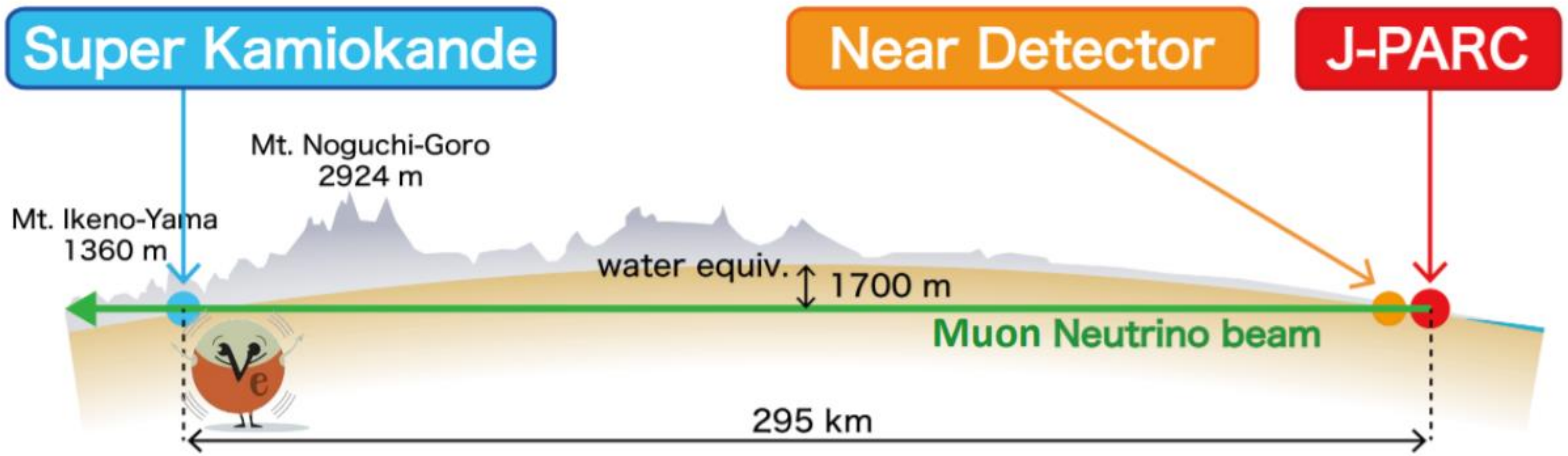




T2K Experiment

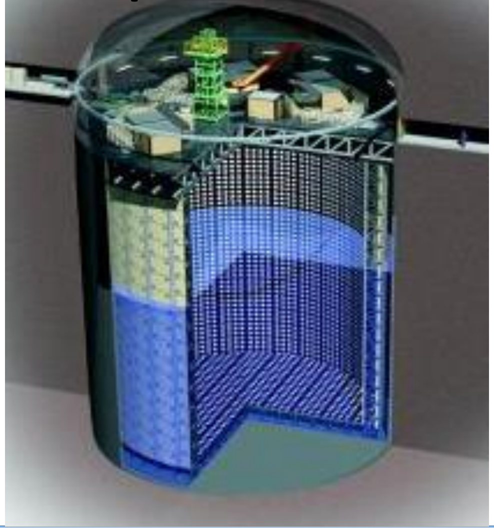
T2K is located in Japan

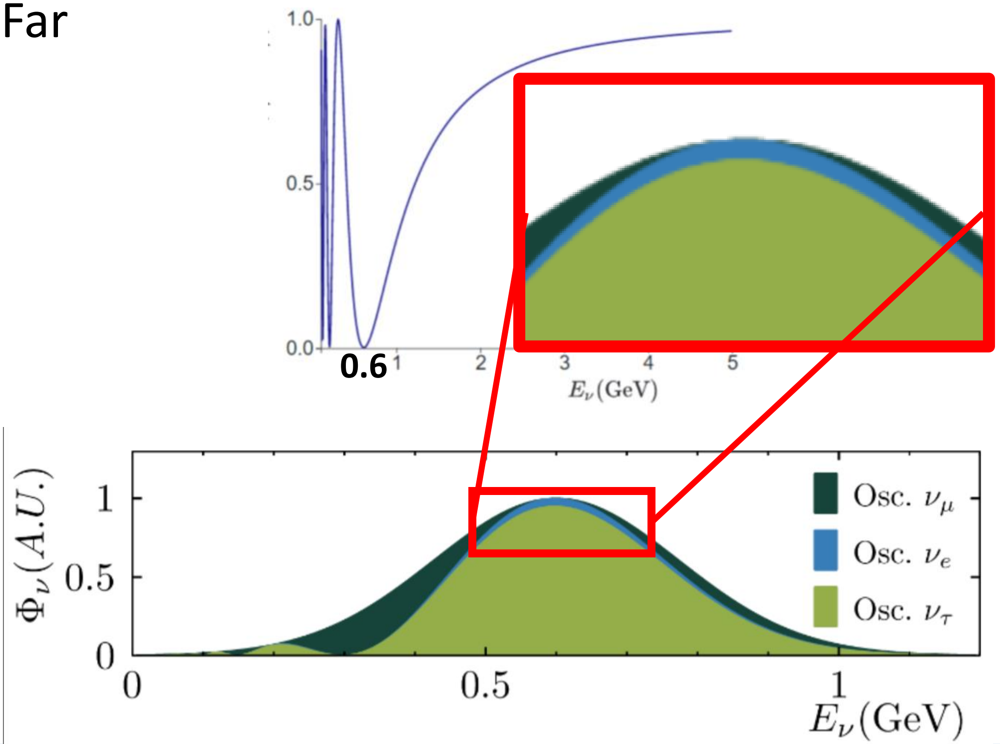
- We create (mostly) muon neutrinos at J-PARC.
  - For neutrino beam modeling we use **NA61/SHINE** data constraints
- We measure neutrinos with Near Detector.
- Neutrinos oscillate.
- Neutrinos are measured in Far Detector

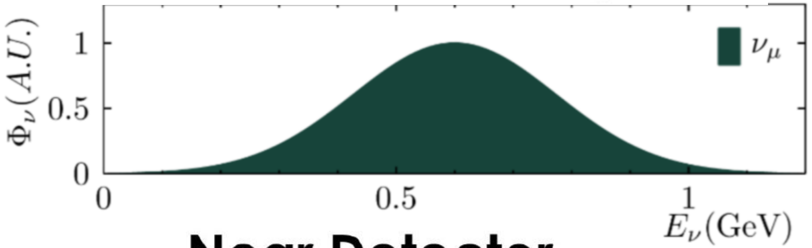


Far Detector

Super Kamiokande

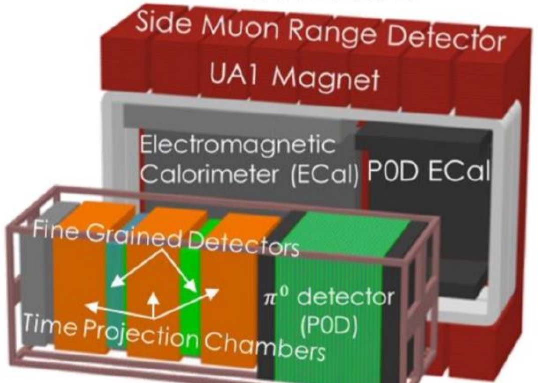






Near Detector

ND280



T2K Oscillation Analysis

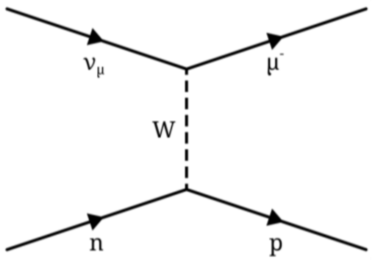
ND280 MC Prediction
(Xsec+Flux+NDdet)

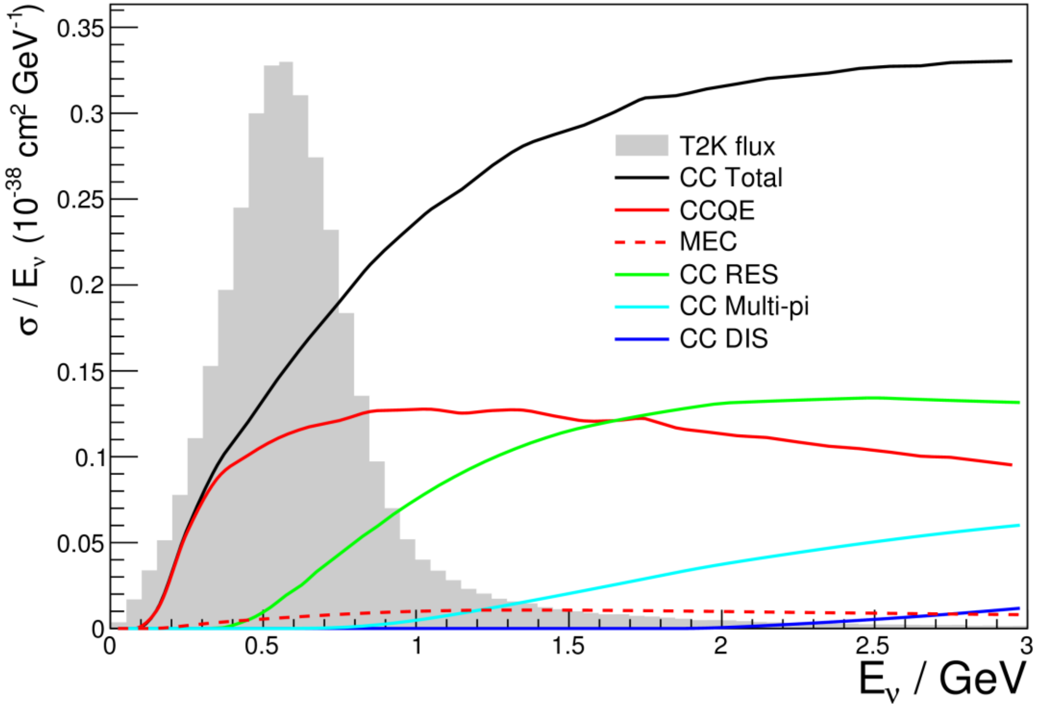
Neutrino Interaction Modeling

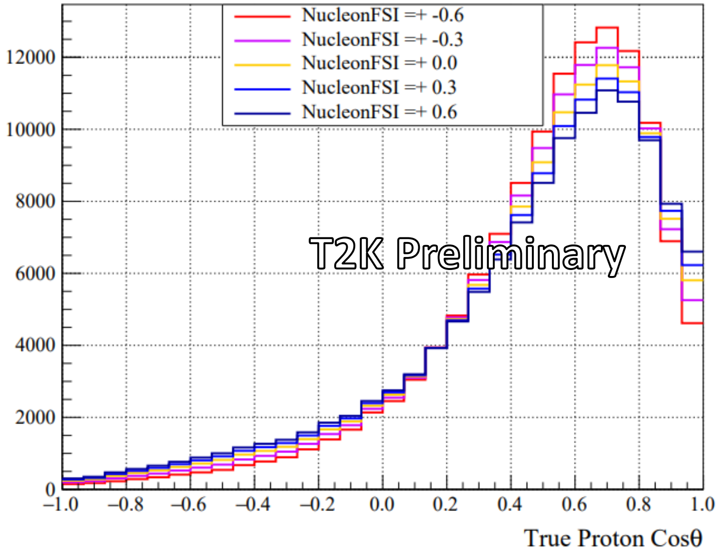
T2K cross-section model includes several reactions, the dominant of which is **CCQE.**

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

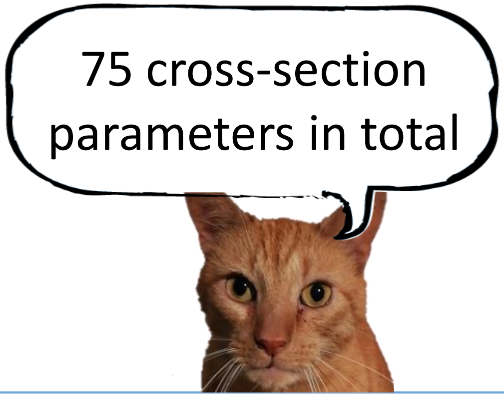
Charge Current Quasi Elastic (**CCQE**)







Kamil Skwarczyński developed two parameters, one of which describes nucleon interaction in the nucleus which impacts proton kinematics.

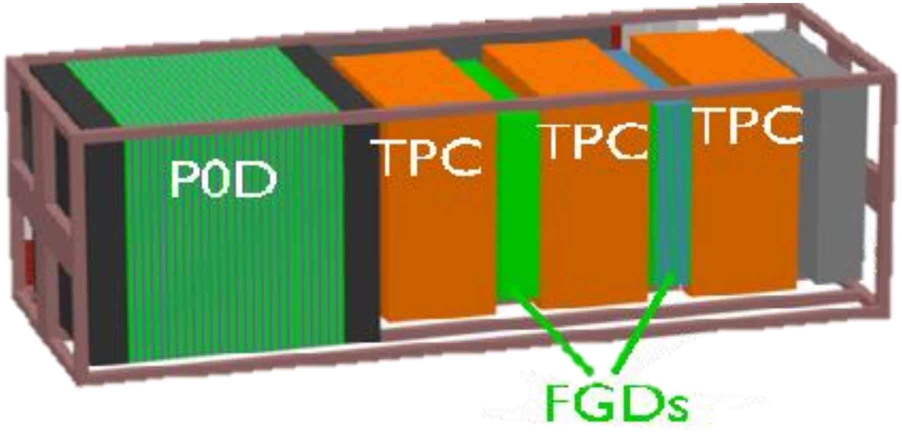


T2K Oscillation Analysis

ND280 MC Prediction (Xsec+Flux+NDdet)

ND280 Data

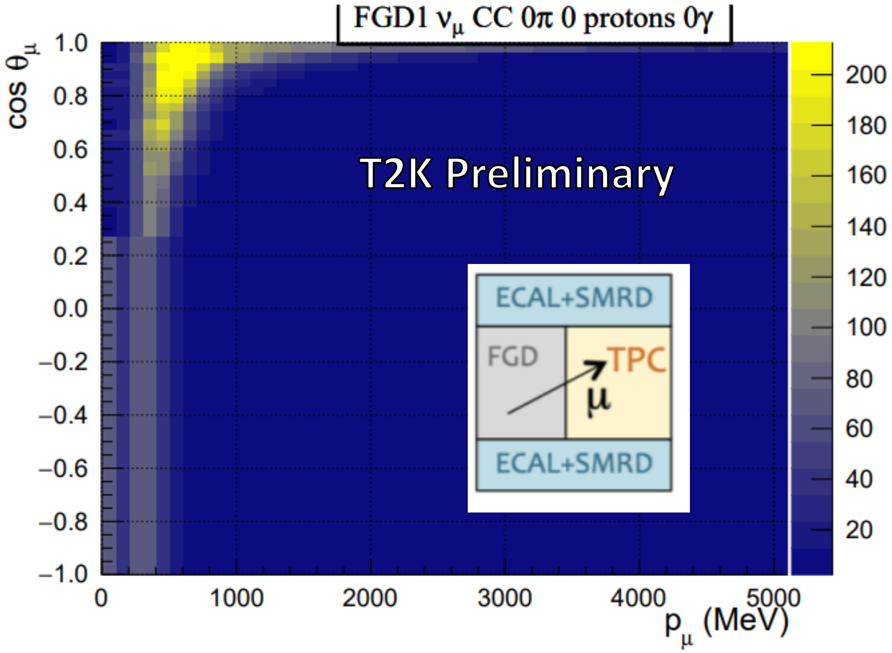
ND280 Samples

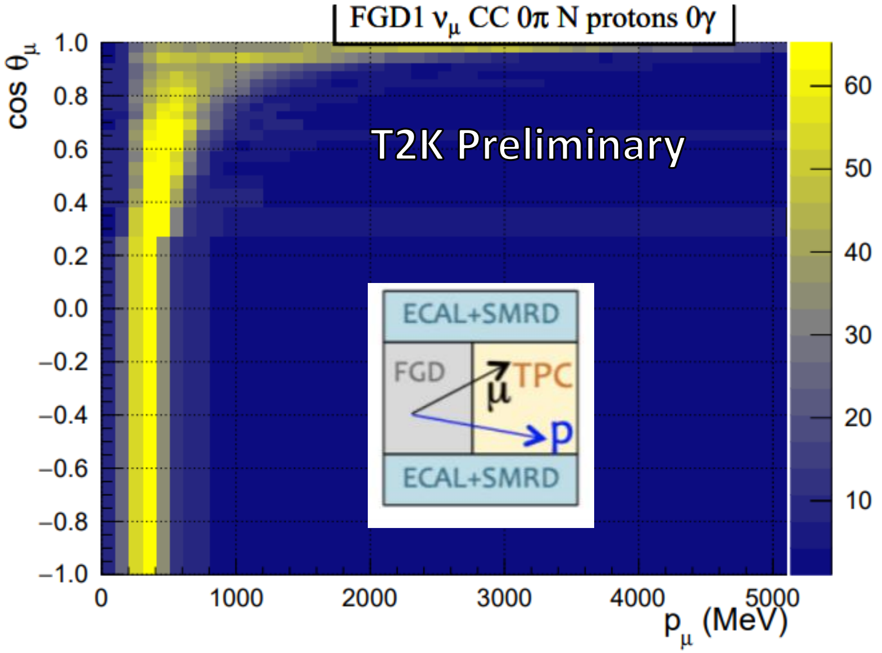


ND280 is used to constrain cross-section and flux models.
Samples are based on reconstructed topology.

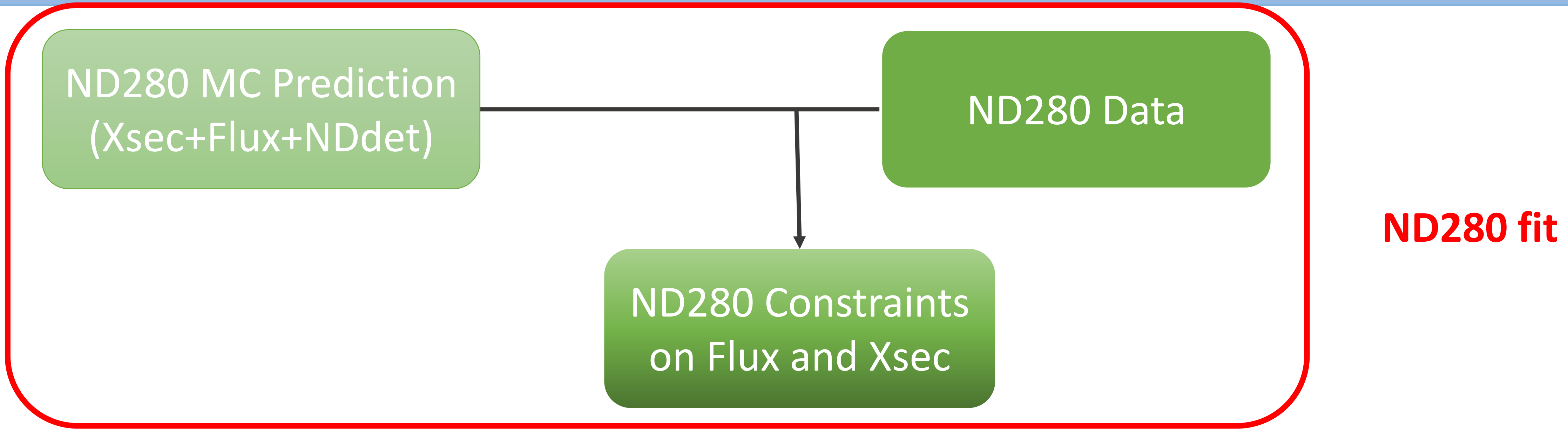
We split data into several samples to better control and constrain various reactions. For example, a sample without reconstructed pions controls CCQE.

Kamil Skwarczyński included four new samples based on proton information.



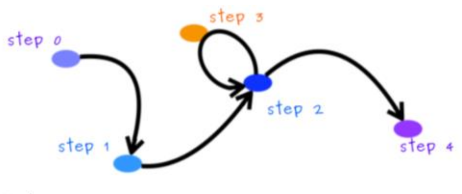


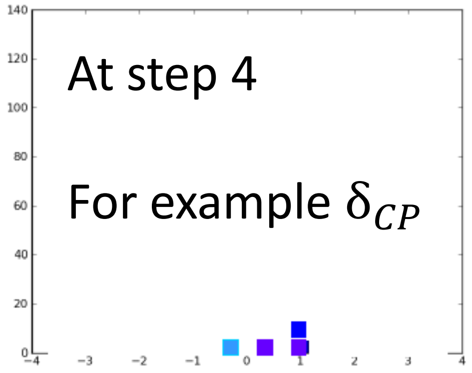
T2K Oscillation Analysis



Markov Chain Monte Carlo

Markov Chain Monte Carlo (MCMC) is an N-dimensional directed random meant to explore parameter space walk, following regions of high likelihood.

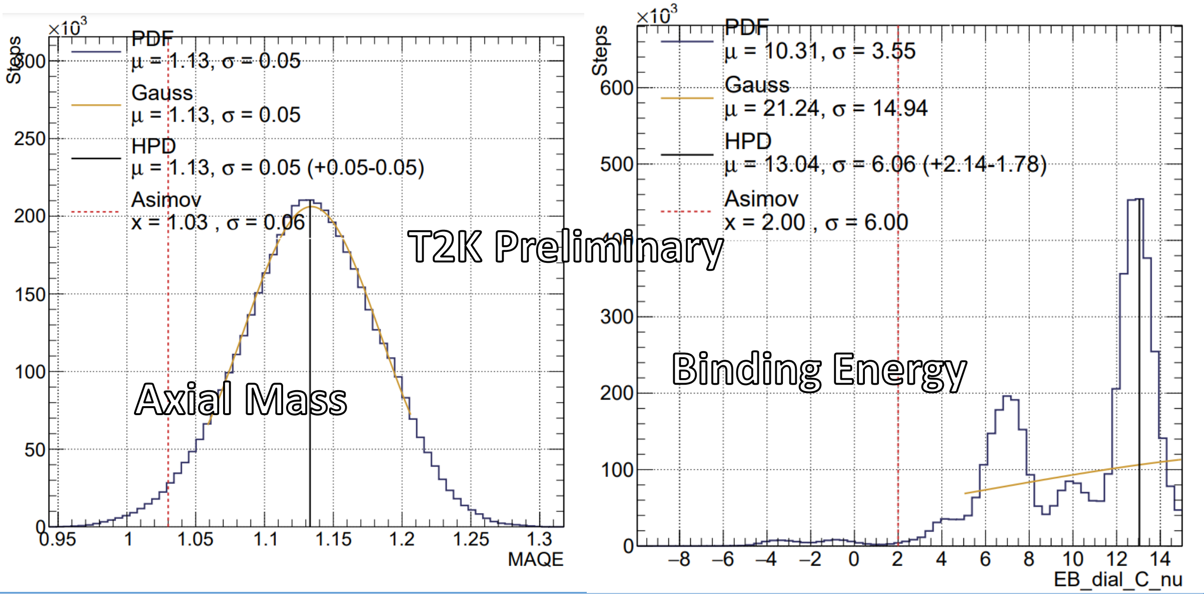




Likelihood tells about data/MC agreement, a step is accepted if the Likelihood is increasing, sometimes we accept a step with lower Likelihood.

Those results are analyzed following **Bayesian** approach.

The main output from the MCMC is a posterior probability distribution.



Impact of ND on FD

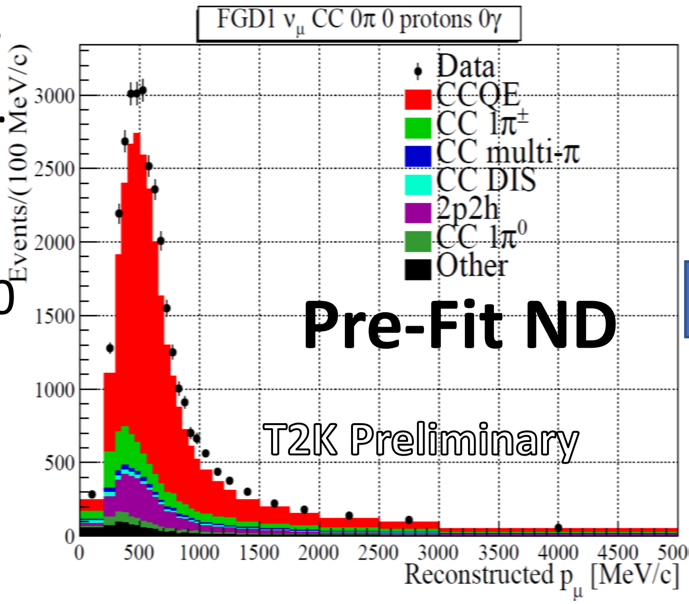
ND280 data is crucial to tune the prior model and shrinking the uncertainties.

Most of the cross-section and flux parameters are shared betweenND280 and FD.

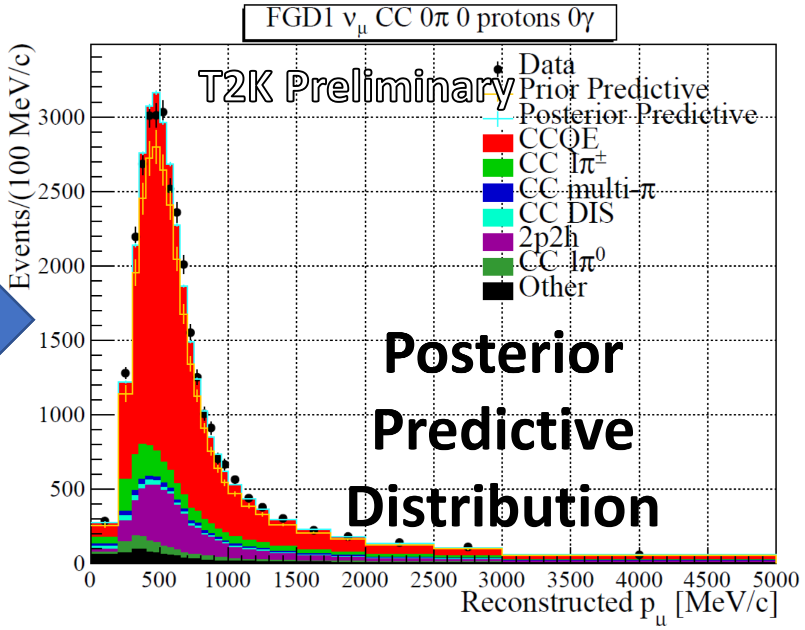
In the final analysis, we run simultaneous ND+FD fit, however, for validation purposes in the Bayesian approach, we also perform ND-only fits.

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

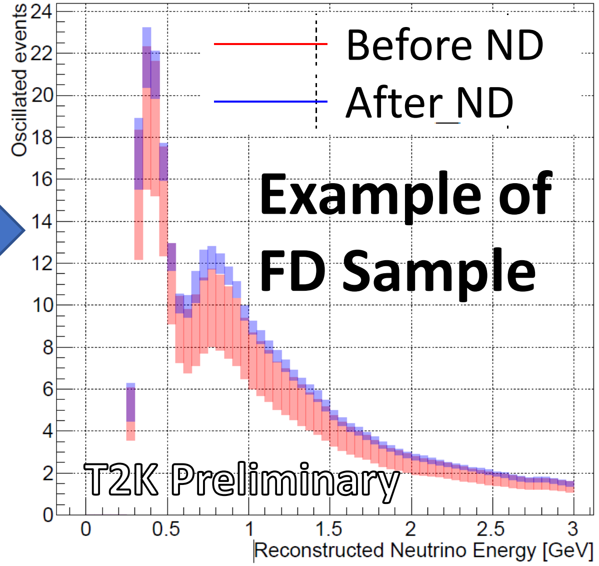
- Smaller error
- Spectrum shape changes, similar as in ND



Data Fit

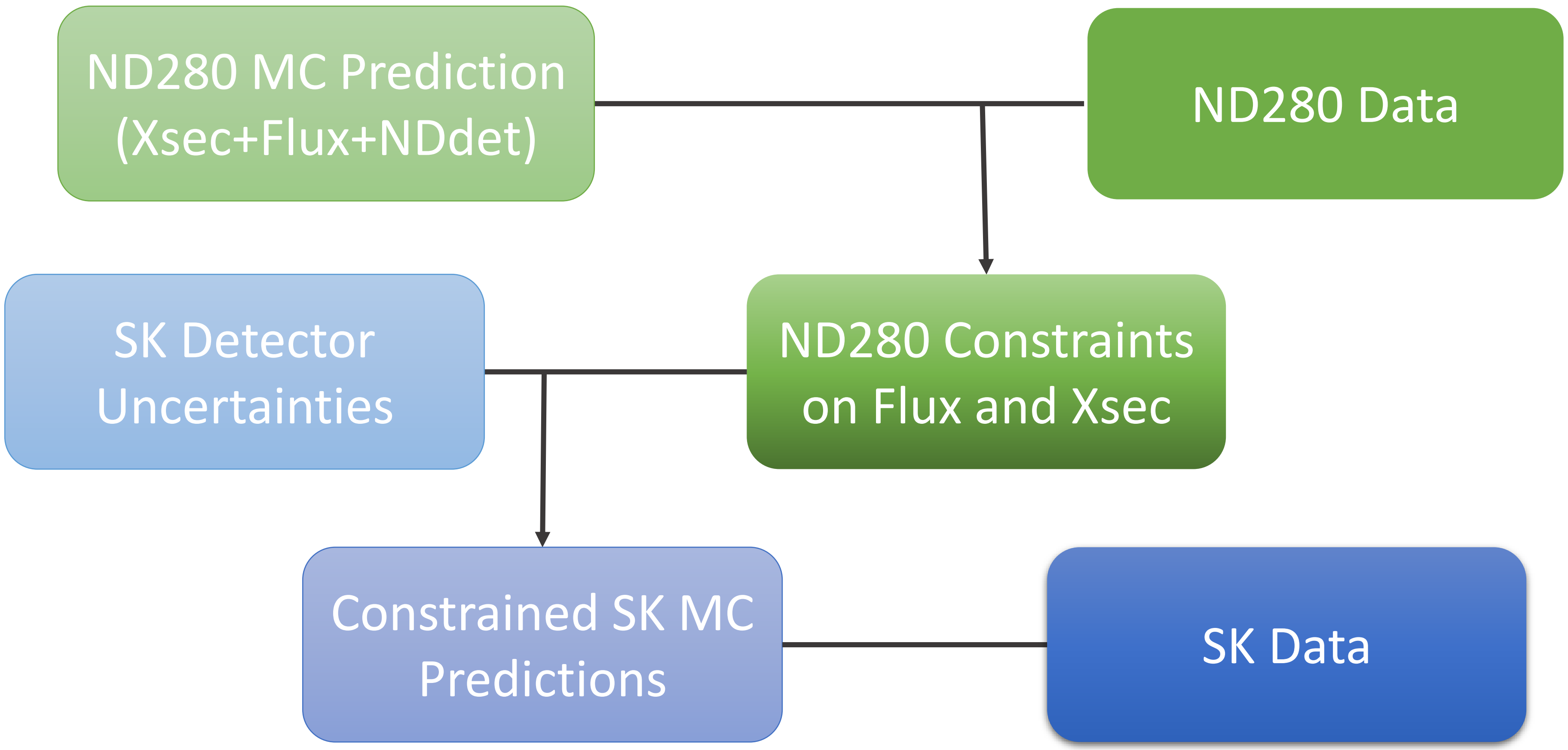


Passing ND constraints to FD

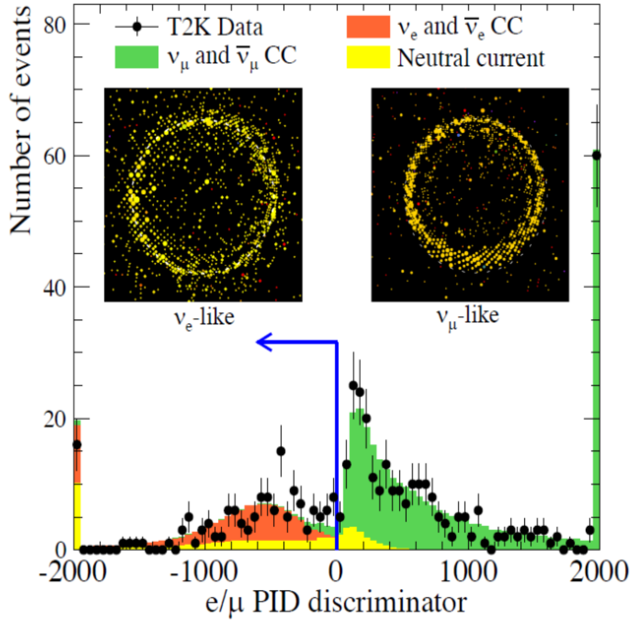


Error on FD event rates reduced by factor 5

T2K Oscillation Analysis



Far Detector Sample

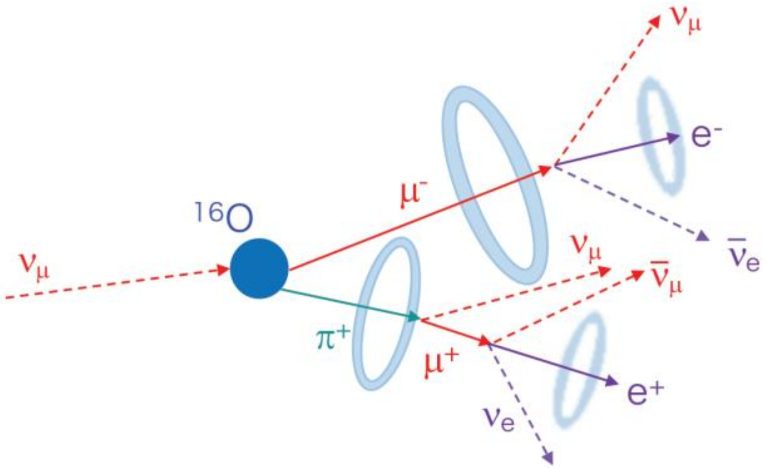


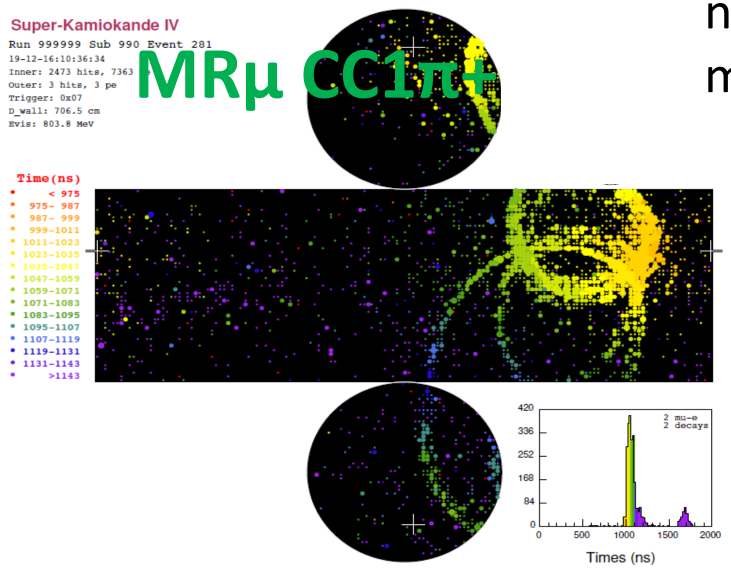
Event samples in Super-Kamiokande (SK) are divided based on the number and type of reconstructed rings.

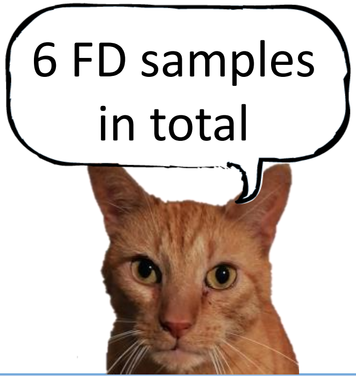
We can differentiate between rings based on their properties like shape.

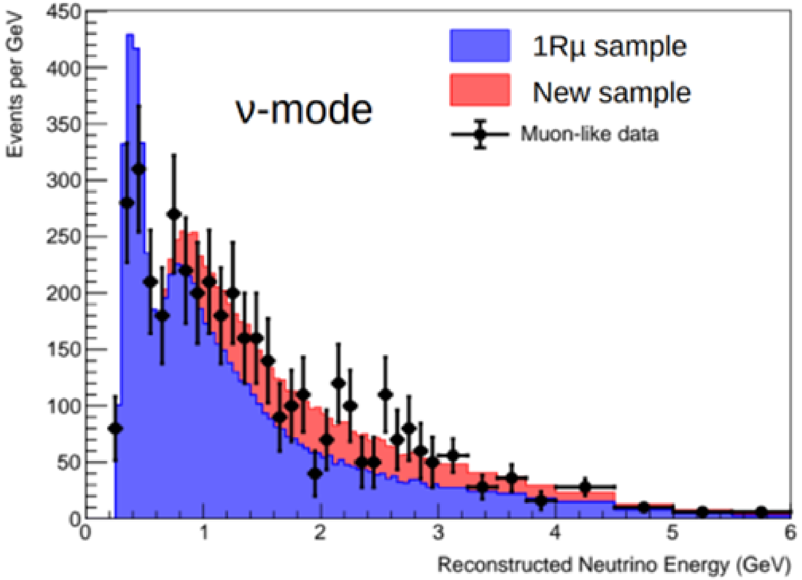
Lakshmi S. Mohan implemented a new sample **MRμ CC1π+**:

- 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.









T2K Oscillation Analysis

ND280 MC Prediction (Xsec+Flux+NDdet)

ND280 Data

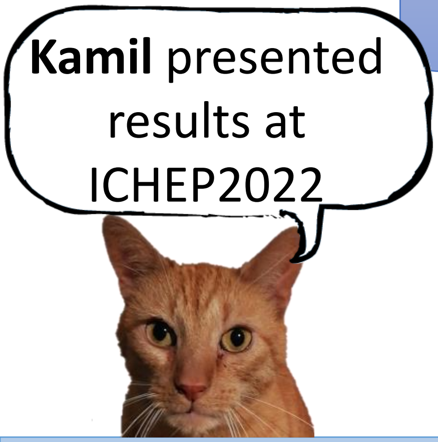
ND280 Constraints on Flux and Xsec

SK Detector Uncertainties

Constrained SK MC Predictions

SK Data

Oscillation Parameters



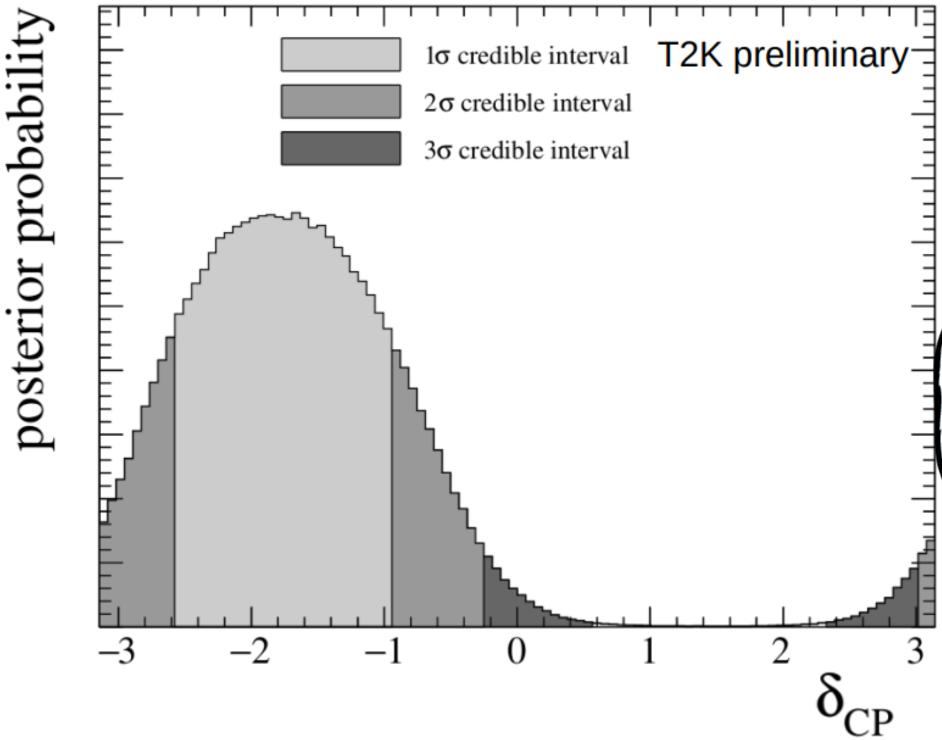
CP Violation?

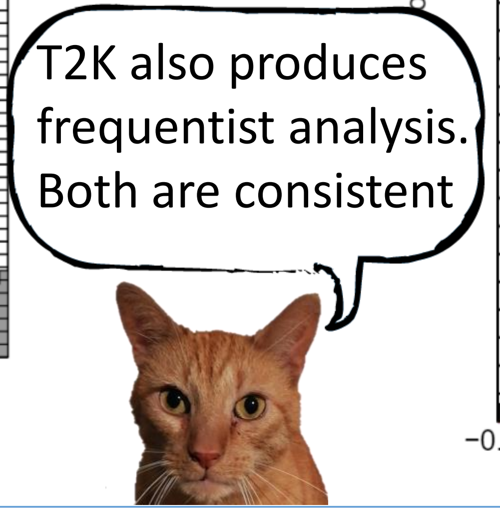
- CP-conserving values of δ_{CP}= 0 and δ_{CP} = π both are outside of 90% CL intervals

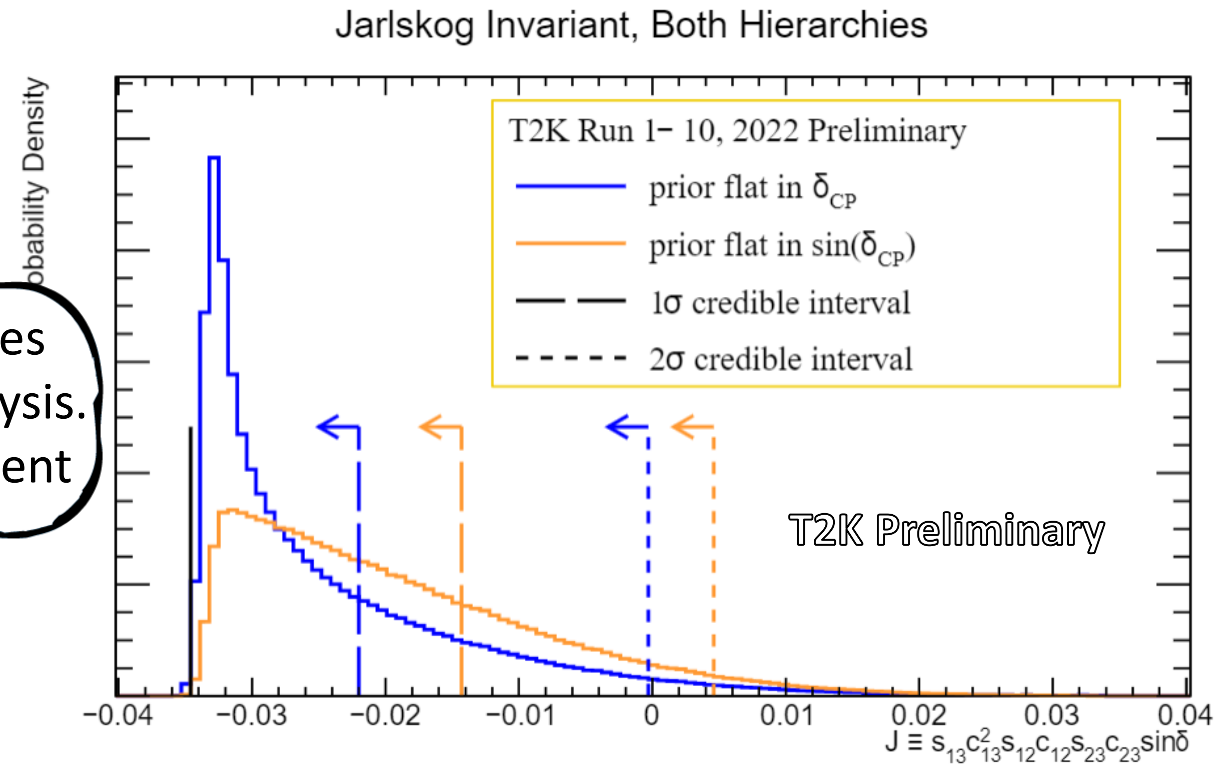
We can perform alternative measurement of CP-violation using Jarlskog invariant.

- Preference for maximal CP-violation independently of prior

Hints of CP violation







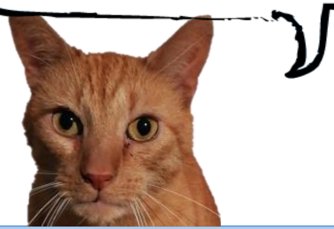
What's next?

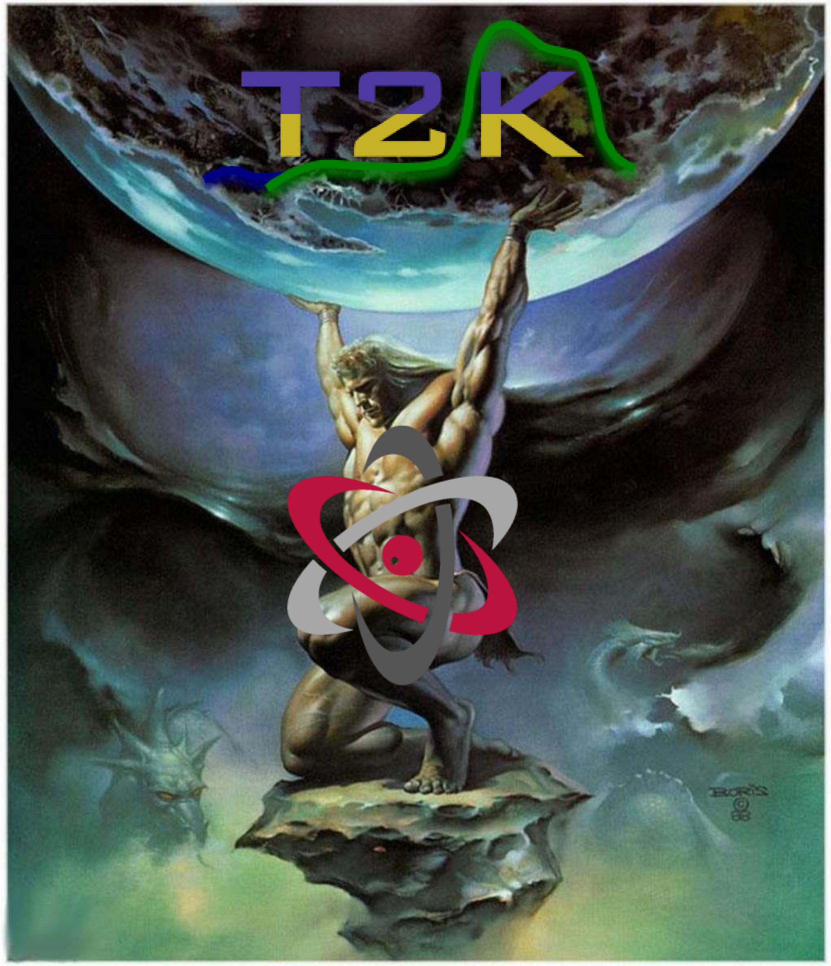
There were 9 technical notes describing this year oscillation analysis.

Kamil and **Lakshmi** was involved in writing 7 out of 9 technical notes while **Justyna Łagoda** was involved in reviewing of 3 TNs. There is only ONE technical note without **NCBJ** involvement.

There are already new **NCBJ** members getting involved to the T2K Oscillation Analysis

Kamil and **Lakshmi** are in the paper committee working on publication

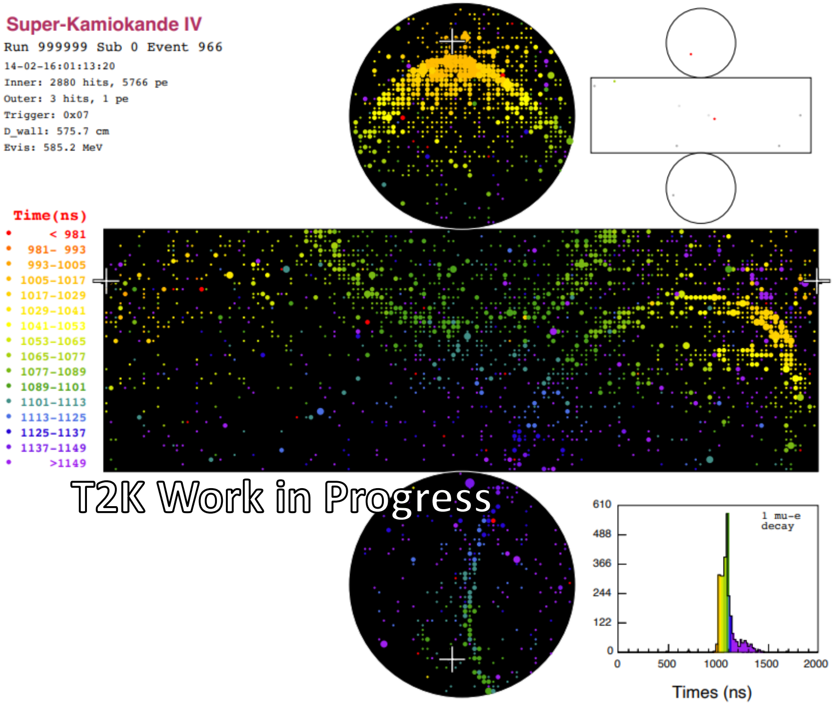


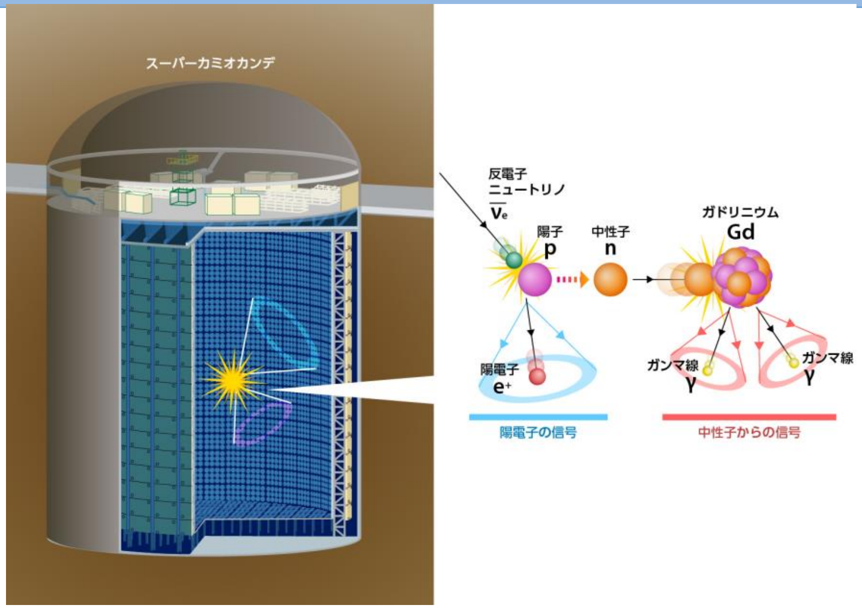


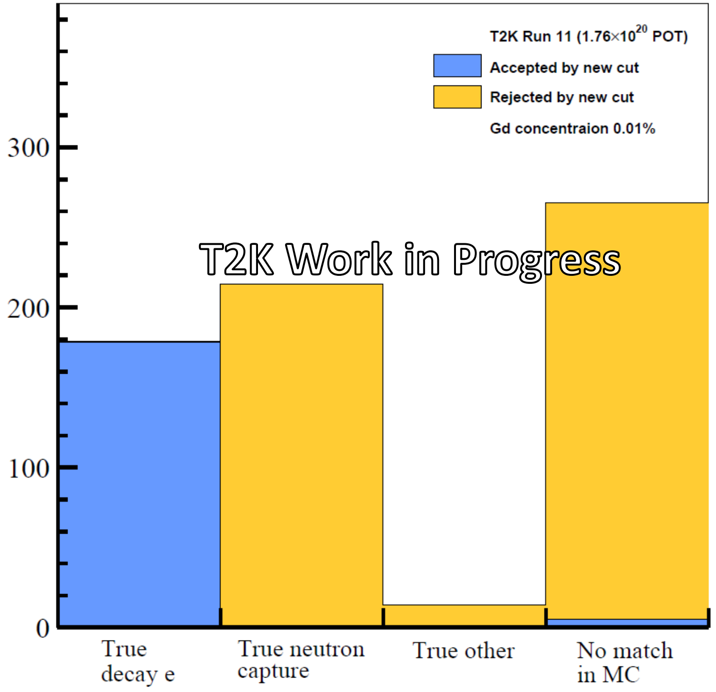
Ongoing Improvements to the Far Detector

Recently gadolinium was added to SK, which will help with neutron detection.

Maitrayee Mandal is working on cut to remove contamination of neutron captures in the decay electron signal.







Yashwanth Prabhu is working on adding new ν_e samples to the SK: $\boldsymbol{\nu_e}$ **CC1π** to increase ν_e statistic by 4% and ν_e CC1π statistics by ~50%.

Maitrayee is also studying $\boldsymbol{\nu_\tau}$

T2K-NOvA Joint-Analysis

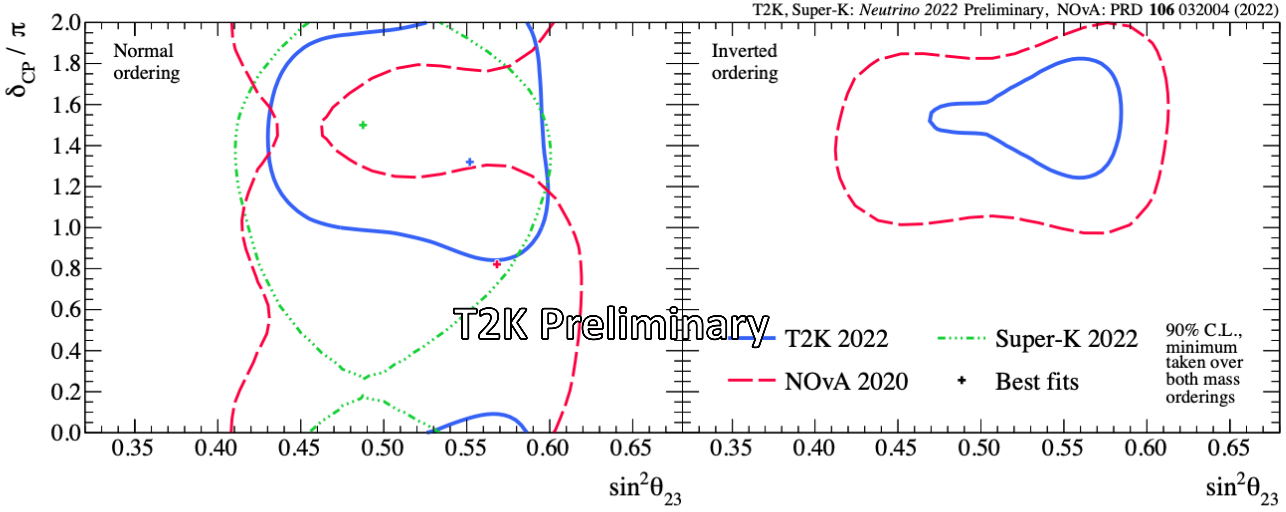
NOvA is another long baseline neutrino experiment in Fermilab.

There is an ongoing analysis between T2K and NOvA.

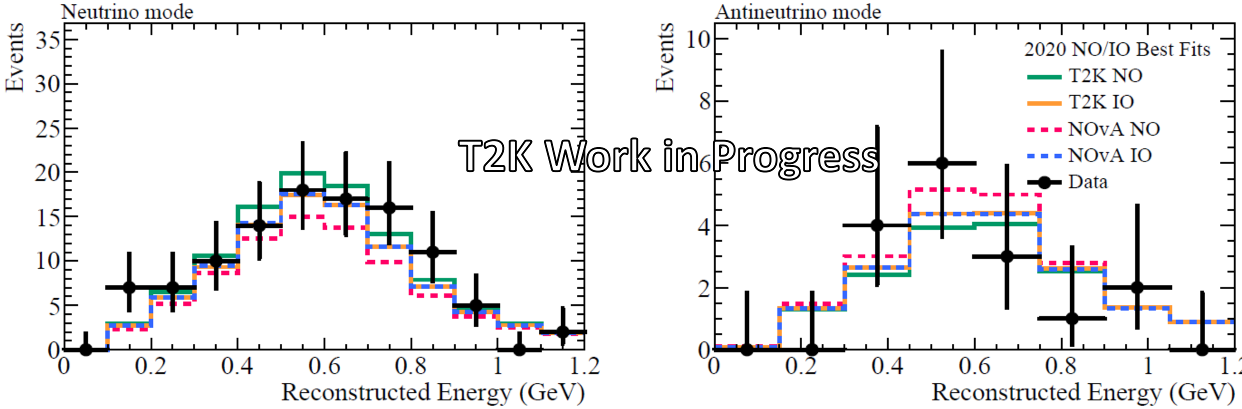
This is the first such joint analysis performed in the neutrino field.

Current studies include assessing the effects of different interaction models

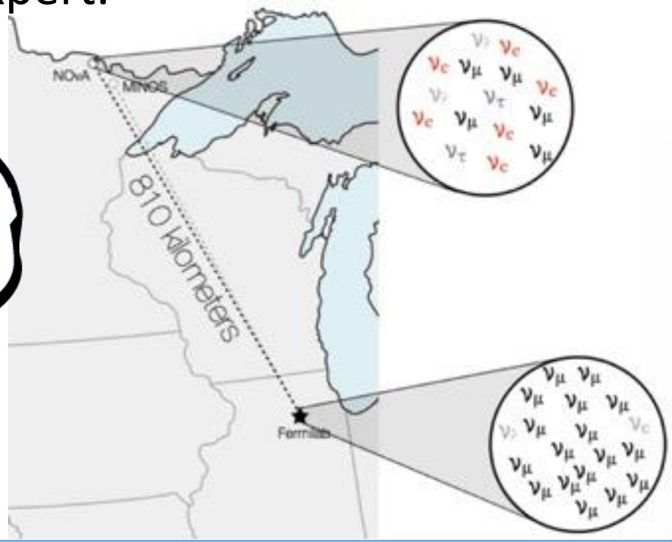
Analysis is expected to converge beginning of **2023.**



Tomas Nosek is helping as a new T2K member and NOvA expert.



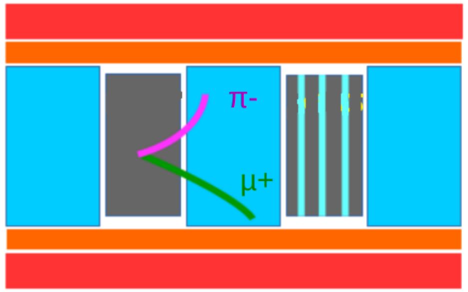
Tomas is also working on reconstruction on one of new ND280 subdetectors

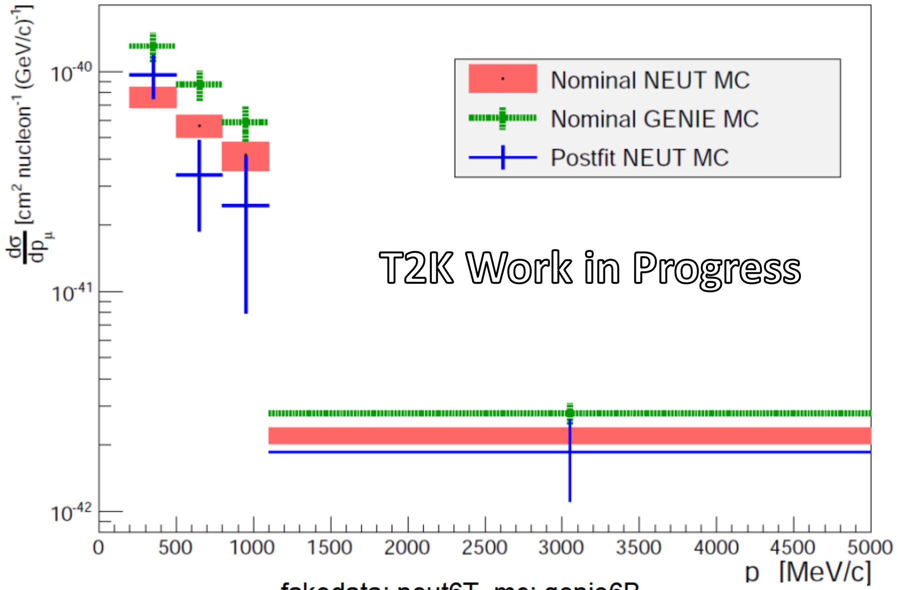


Cross-Section Measurements

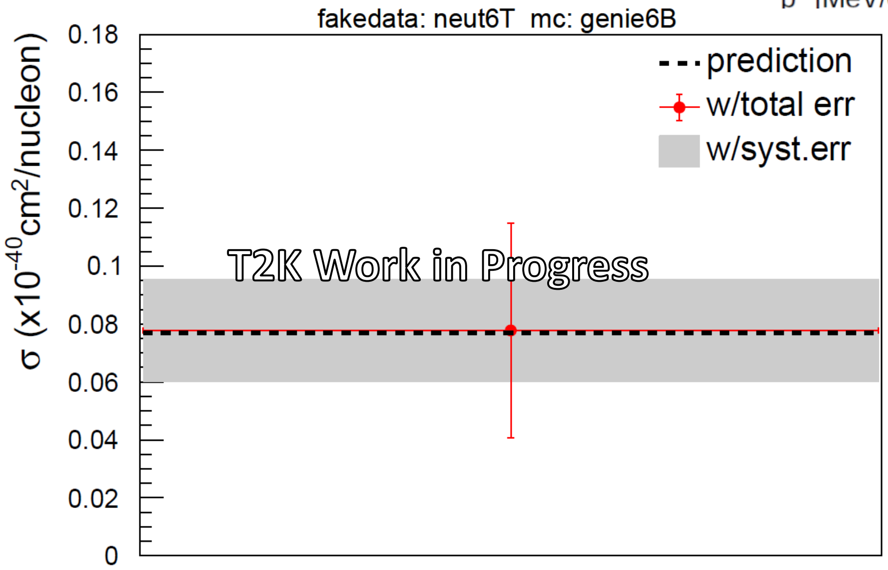
NCBJ group is involved as well in cross-section analysis as well

Grzegorz Żarnecki studied cross-section of π^- production by antineutrinos.
He defended his PhD **06.2022**





Katarzyna Kowalik is measuring cross section of K+ production in the muon neutrino interactions. Expected ~25 signal events. The data results are coming in the year **2023**.



Joanna Zalipska is studying low-energetic particles with the calorimetric measurement

Summary

Ewa Rondio

Justyna Łagoda
Joanna Zalipska
Katarzyna Kowalik
Piotr Mijakowski

Post-Docs
Lakshmi S Mohan
Tomasz Nosek

PhD Students
~~Grzegorz Żarnecki~~ (NCBJ->IFJ)
Piotr Kalaczyński
Kamil Skwarczyński
Maitrayee Mandal
Yashwanth S Prabhu

Magda Posiadała-Zezula

New T2K results:
- Improved cross-section uncertainties, including nucleon interactions in nuclei
- 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.

Other activities

SK
- Atmospheric ν_τ oscilattions

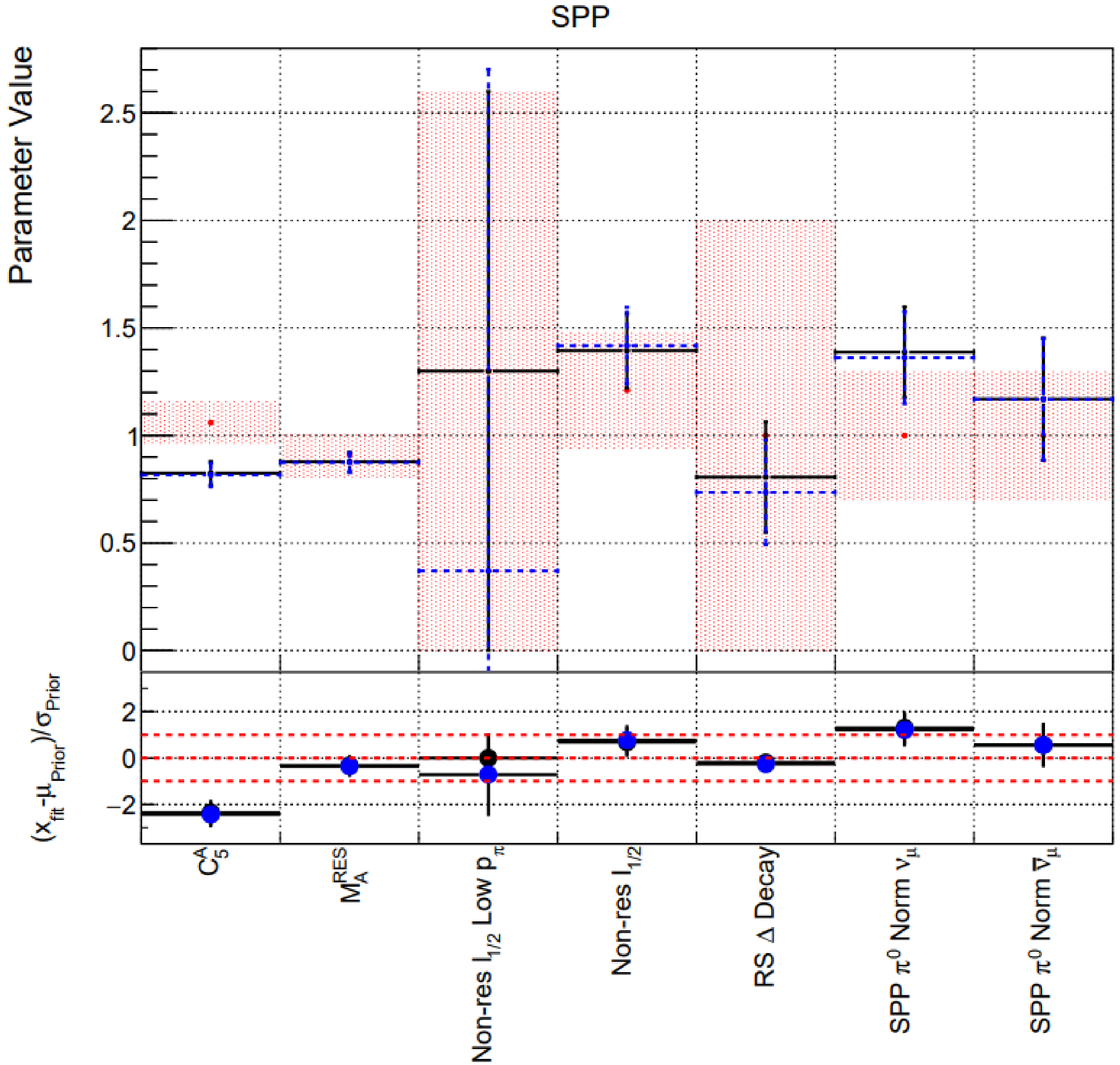
KM3NET
- Cosmic Ray muon simulations and reconstruction of muon bundle properties.
- Analysis of the prompt component of the atmospheric muon spectrum

Group supported by:
Ongoing: Sonata bis, MSCA-RISE Jennifer II, MSCA-RISE SK2HK, Preludium
Finished in 2022: T2K ministerial grant
In review: HK ministerial grant

Polish Neutrino Group Meeting
Warsaw 04.2022

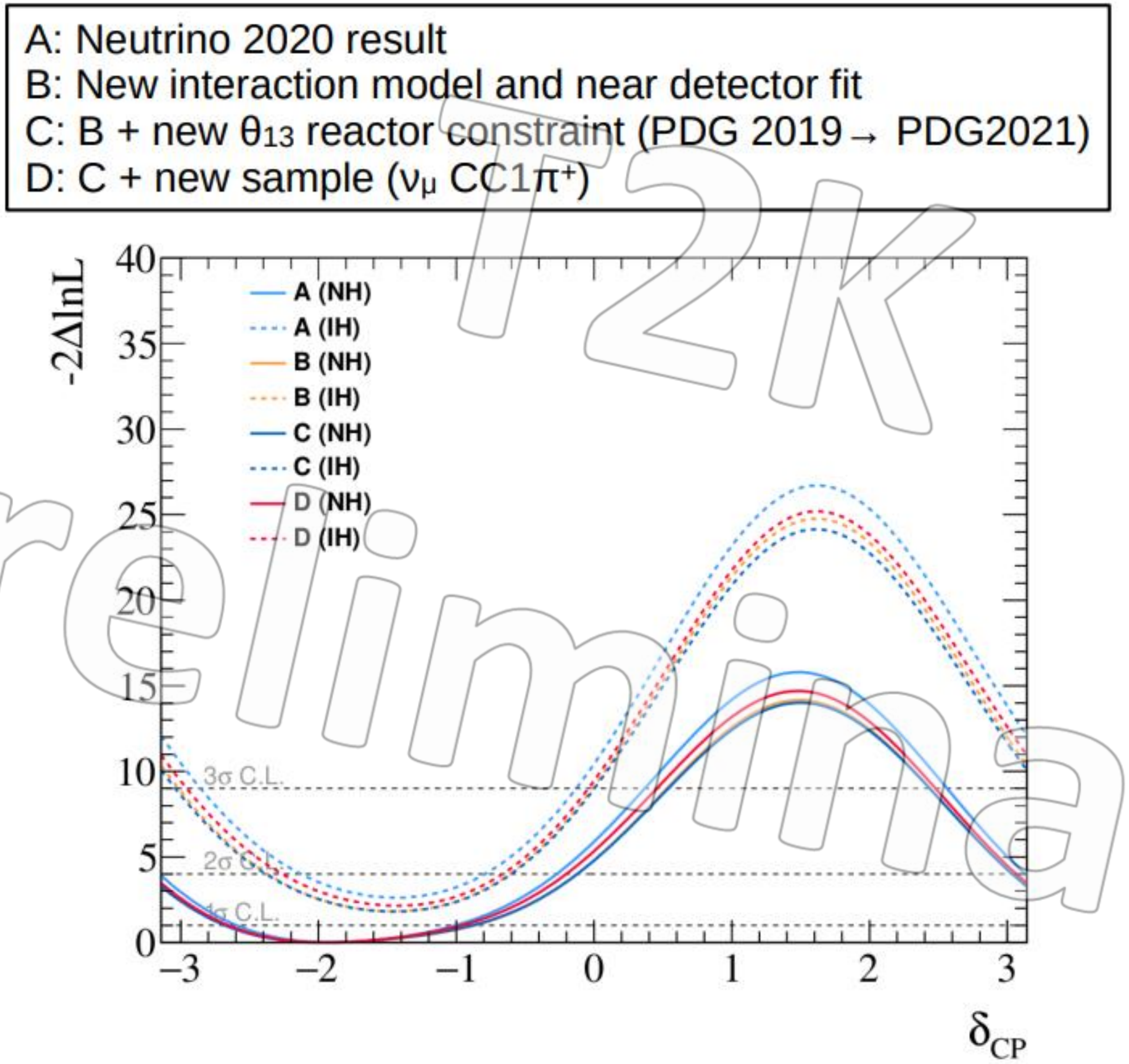
Backup

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 $\bar{\nu}_\mu$

Effect of Analysis Change

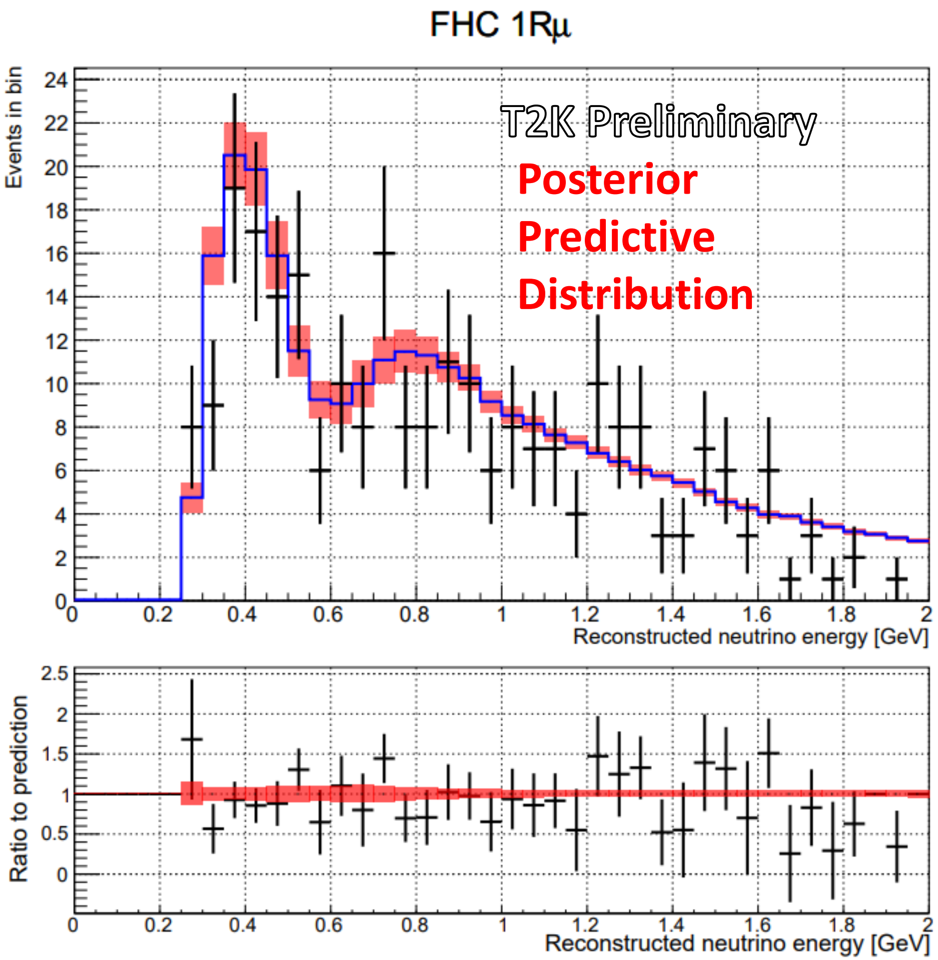


Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

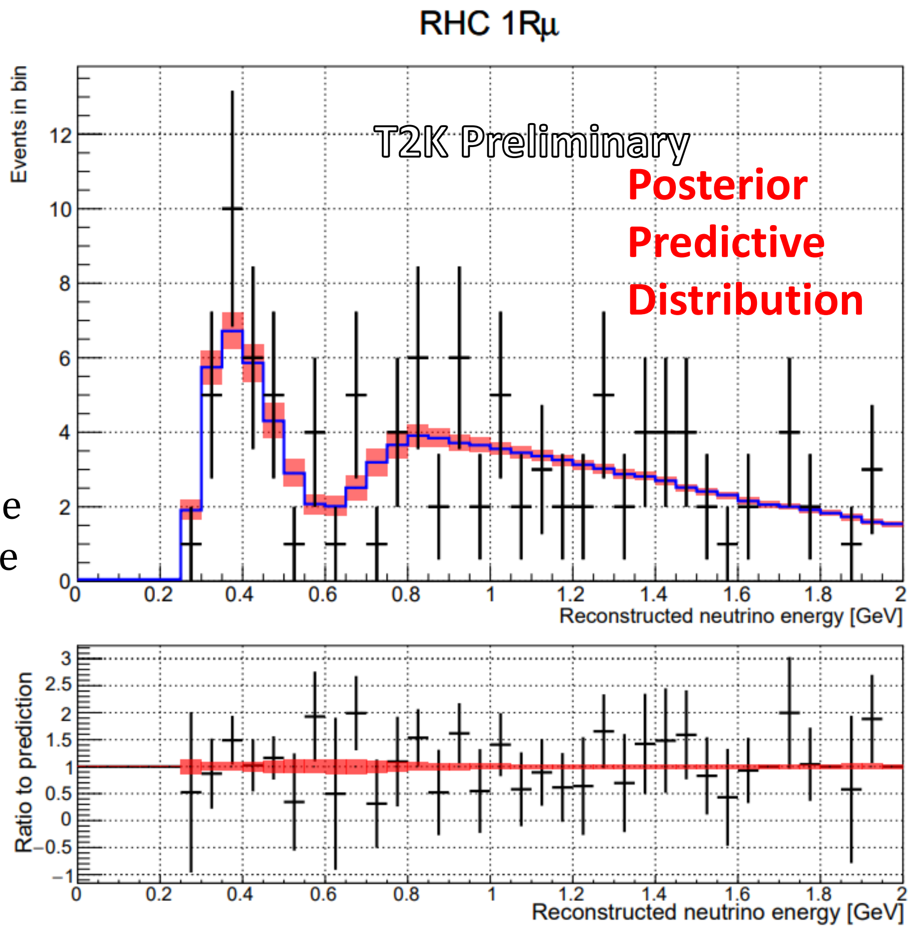
ND+FD Results

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

Although the statistical error is quite high.

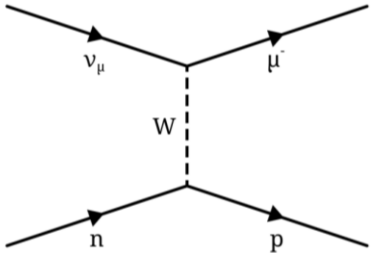


Forward Horn Current (**FHC**) - ν mode
Reverse Horn Current (**RHC**) - $\bar{\nu}$ mode

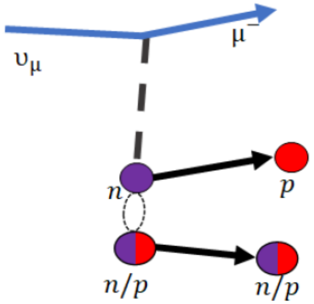


T2K Cross-Section model

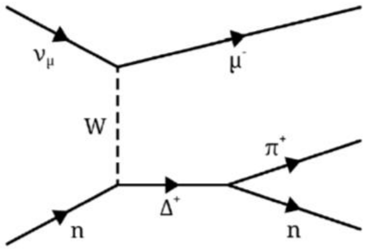
Charge Current Quasi Elastic (**CCQE**)



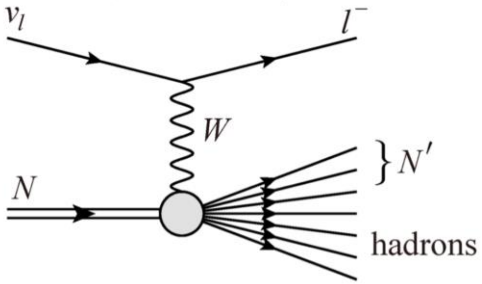
Two Particles Two Holes (2p2h or MEC)



Resonant Scattering (**RES**)

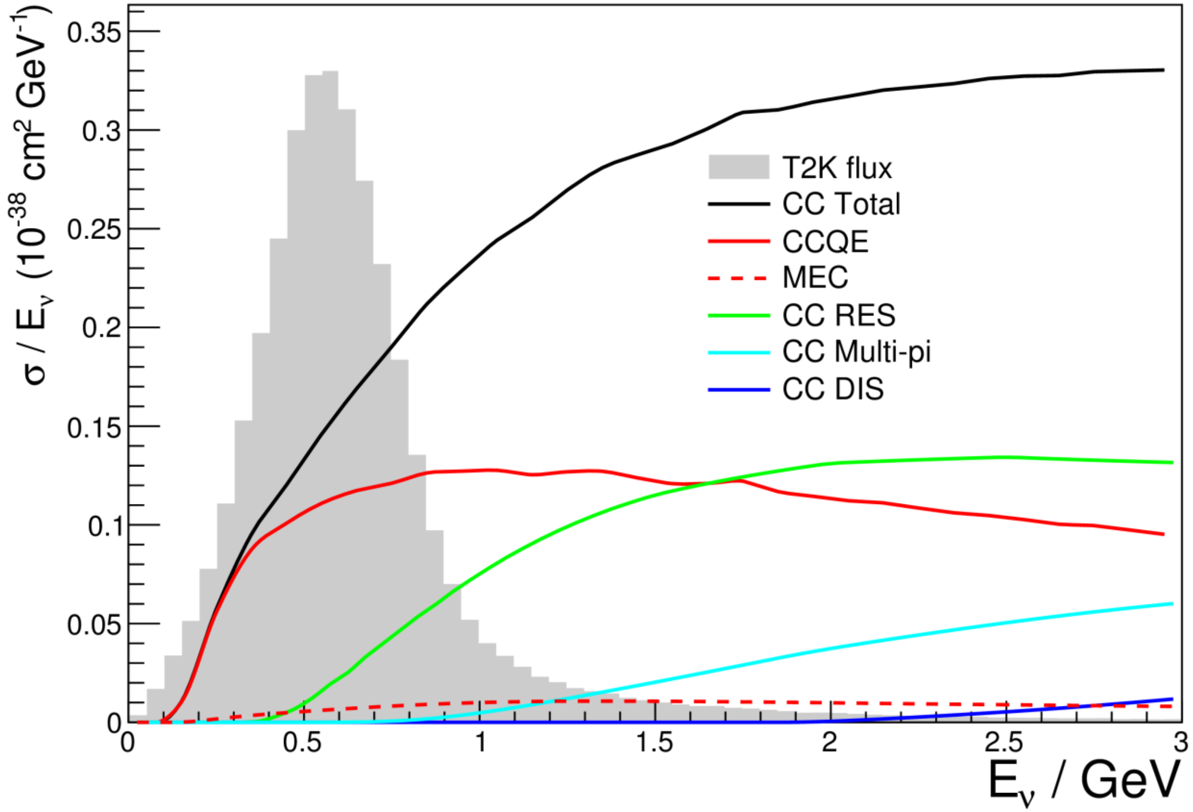


Deep Inelastic Scattering **(DIS)**
and Multi-pi production



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.



CC Photon

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

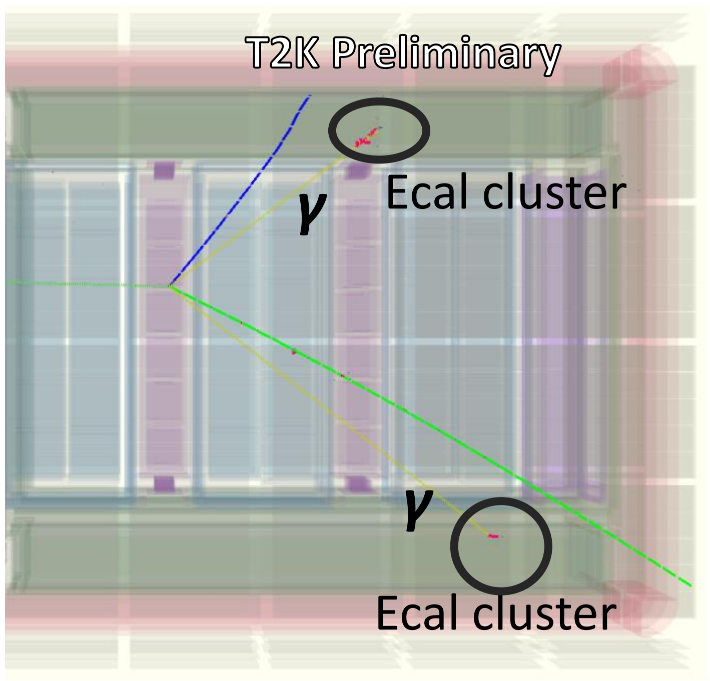
$$\pi^0 \rightarrow \gamma + \gamma$$

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

$$\eta \rightarrow \gamma + \gamma$$

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

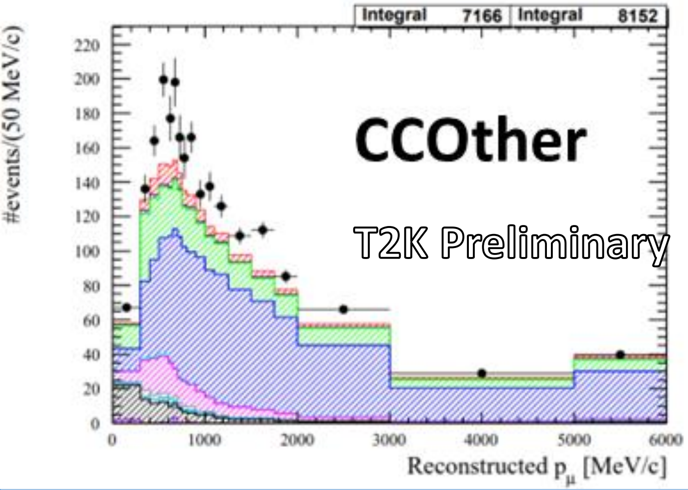
$$K \rightarrow \pi^0 + X \rightarrow \gamma + \gamma + X$$

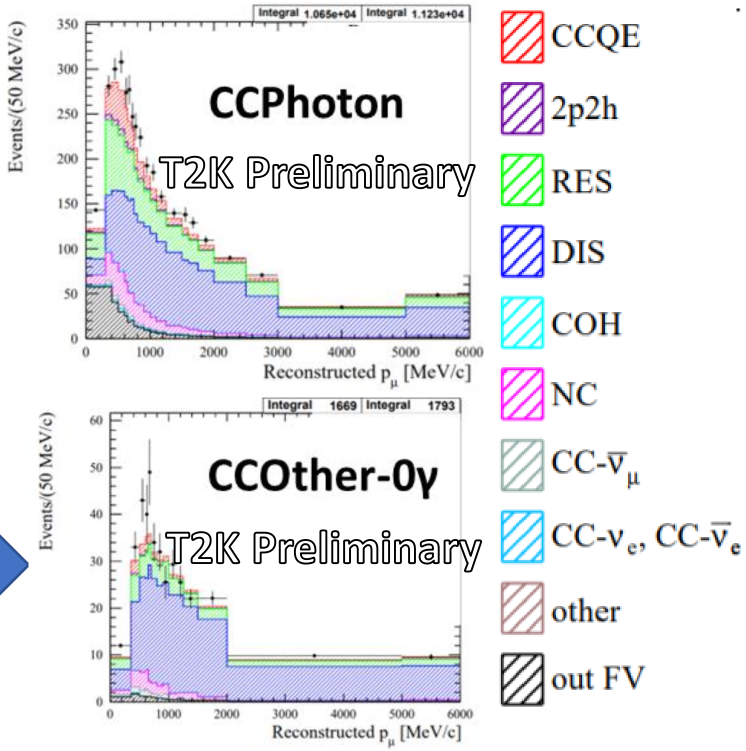


New CC Photon sample takes into account events with reconstructed photon object in the ECal.

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.

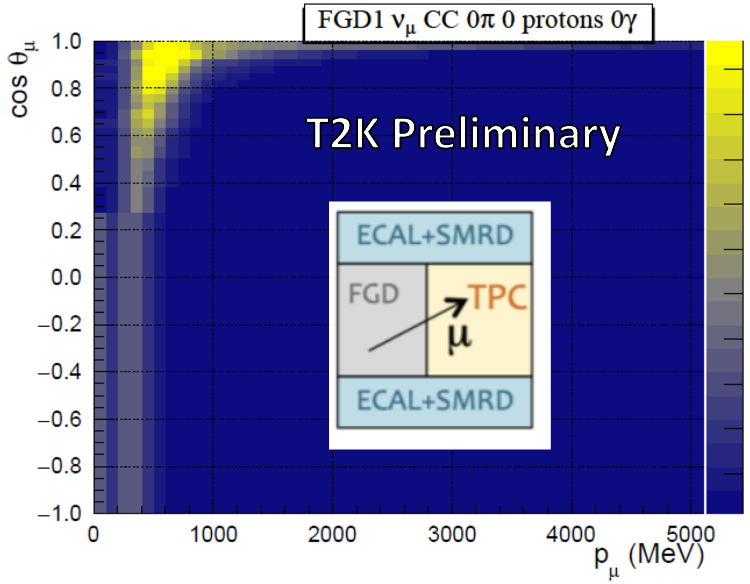
The biggest advantage of this sample is making CC Other more enhanced with **DIS** events

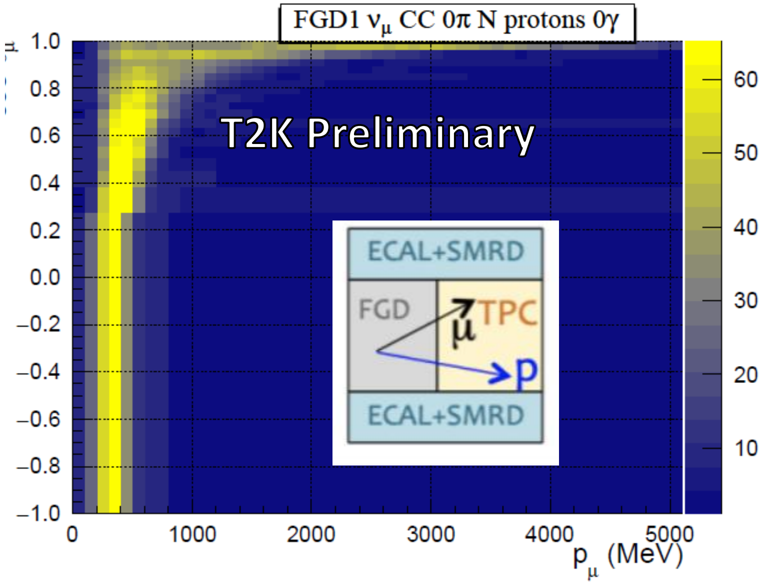
Proton Samples

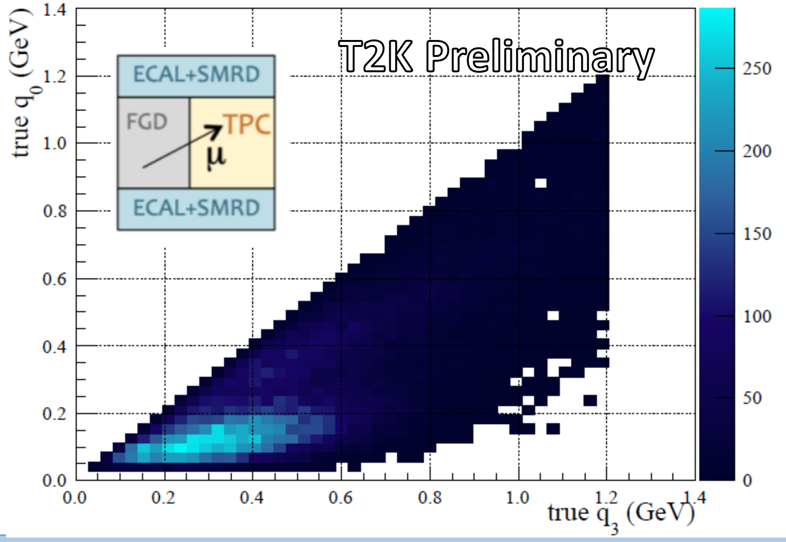
Previous CC0pi sample has been split into:

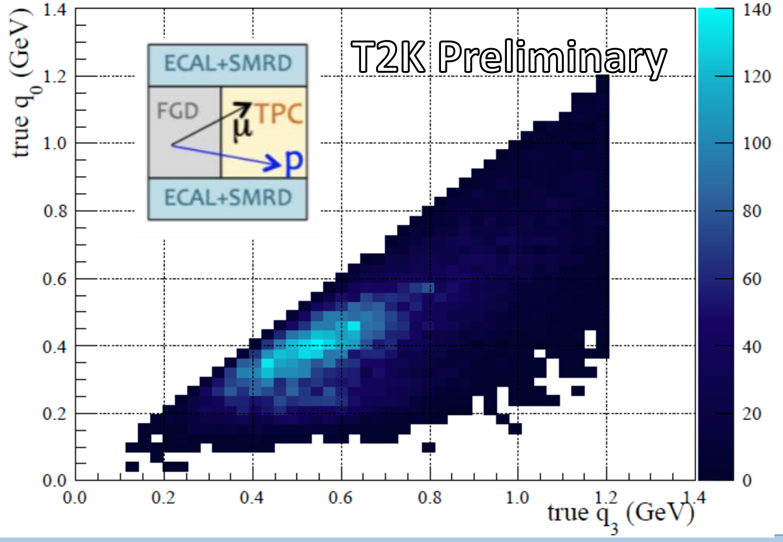
CC0pi-0p – no protons
CC0pi-Np – at least one proton

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





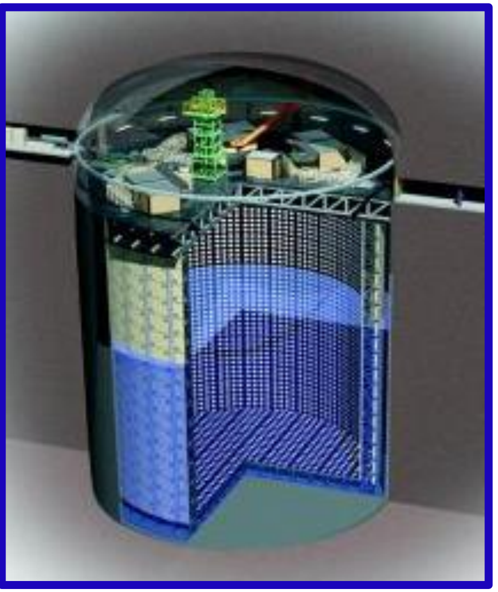




Proton-tagged samples have been implemented only in neutrino mode.

Energy transfer:
$$\boldsymbol{q_0} = E_\upsilon - E_\mu$$
Momentum transfer:
$$|\vec{\boldsymbol{q}}_{\boldsymbol{3}}| = |\vec{p}_\upsilon| - |\vec{p}_\mu|$$

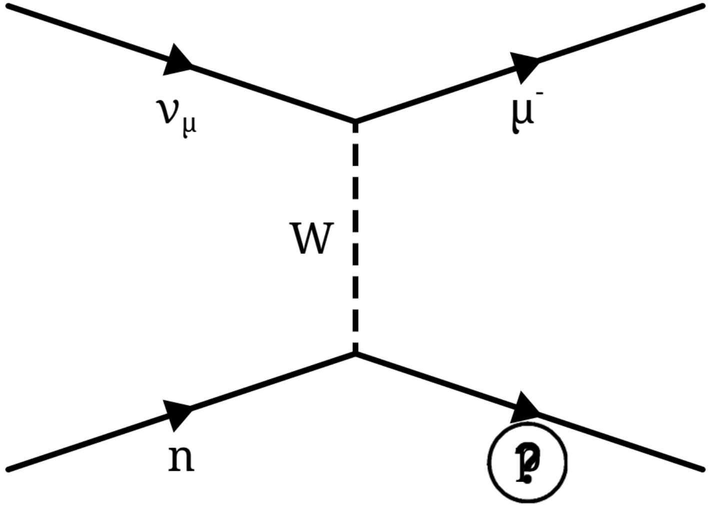
Far Detector Samples

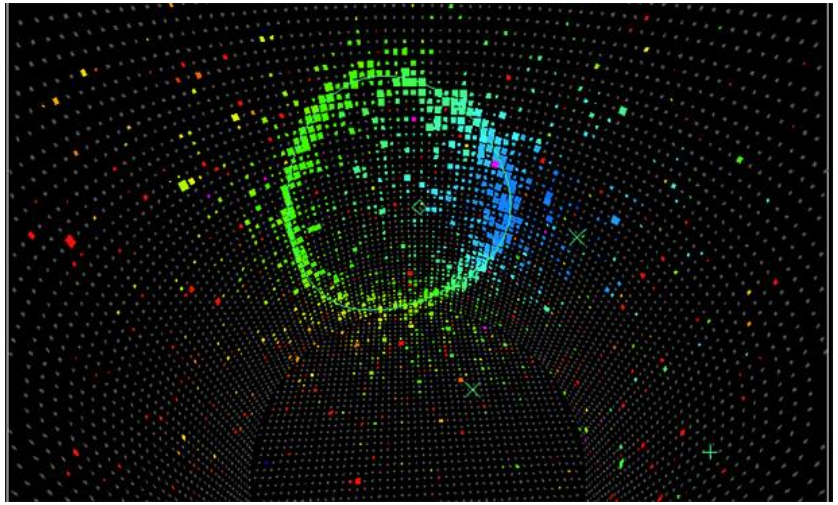


Super-Kamiokande (SK) is a water Cherenkov detector.

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

Energy reconstruction using alternative method.

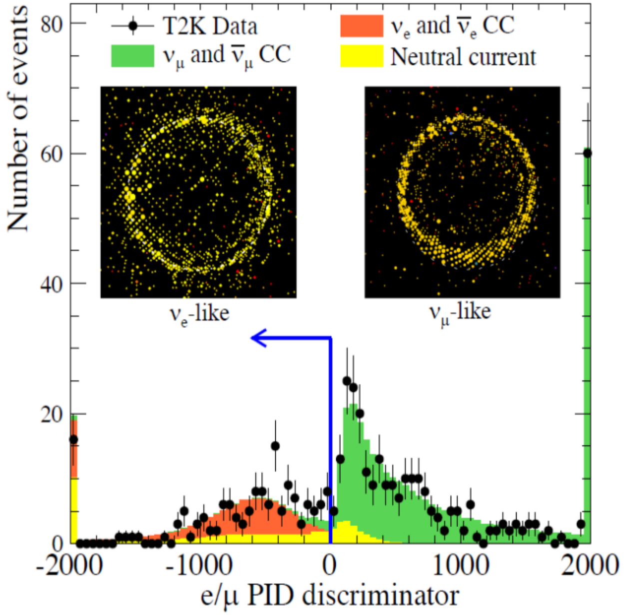




$$E_{\upsilon}^{rec} = \frac{m_p^2 - (m_n - E_B)^2 - m_e^2 + (m_n - E_B)E_l}{2(m_n - E_B - E_l + p_l cos\theta_l)}$$

Only uses particle masses, lepton kinematics and nuclear model.

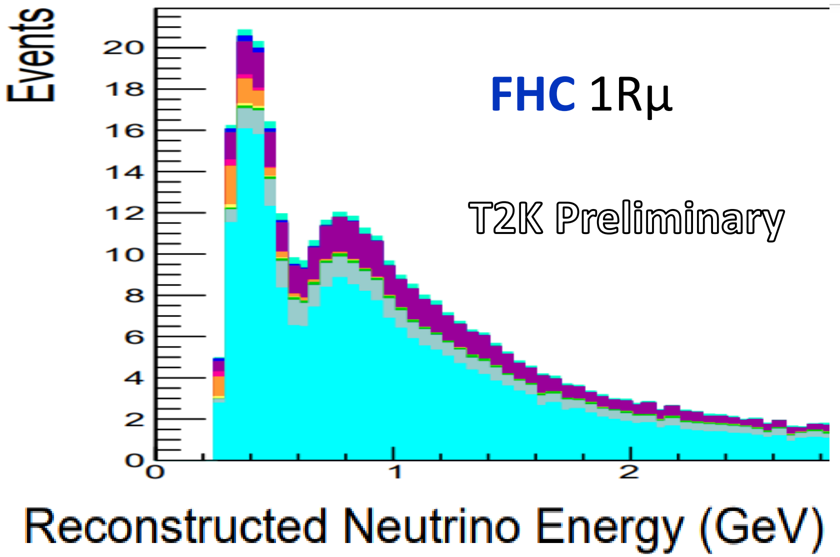
Super-Kamiokande Selection



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

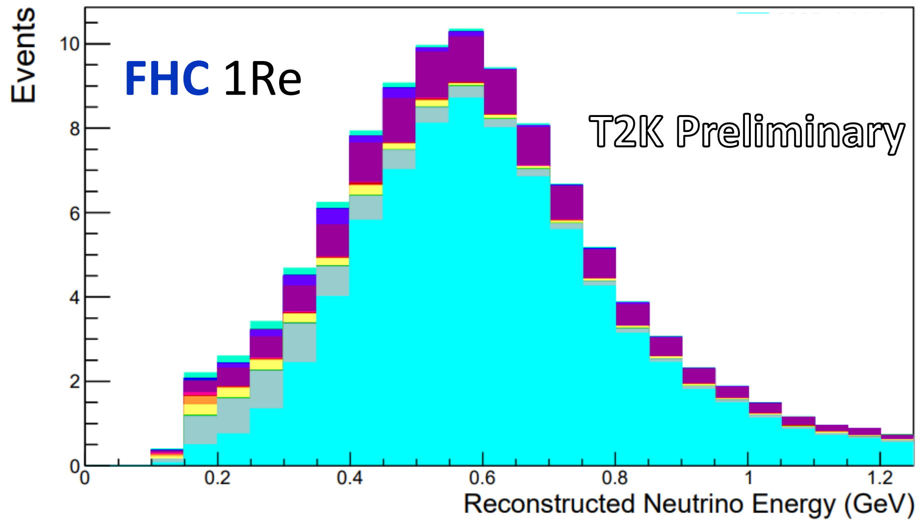
We can differentiate between rings based on its properties like shape.

A similar set of samples are for FHC and RHC.



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

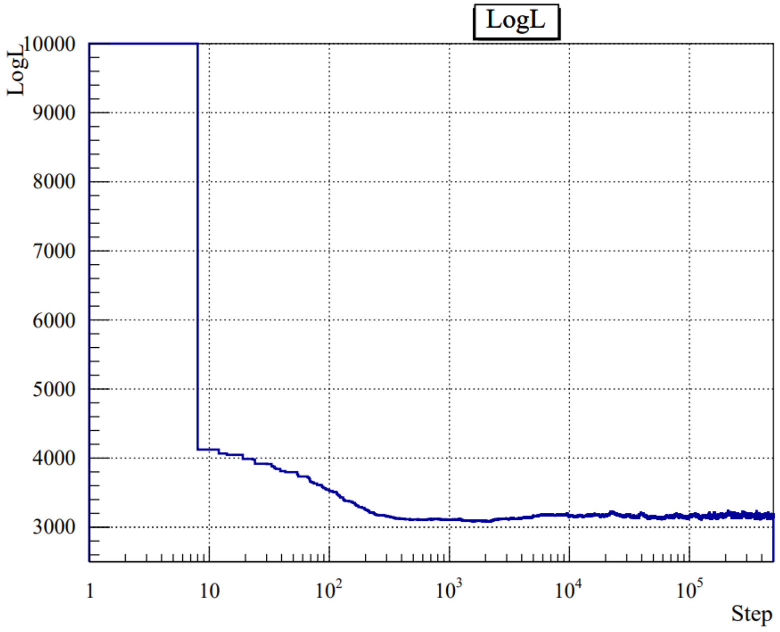
Mode	Sample Name	Description
$\boldsymbol{\nu}$	**1Re**	One e-like ring in $\boldsymbol{\nu}$ mode
	1Re CC1π+	One e-like ring and Michel electron in $\boldsymbol{\nu}$ mode
	1Rμ	One μ-like ring in $\boldsymbol{\nu}$ mode
	MRμ CC1π+ (Multi-Ring)	New! (next slide)
$\bar{\boldsymbol{\nu}}$	**1Re**	One e-like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



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



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

LLH for ND-only fit.