T2K Near Detector fit using Markov Chain Monte Carlo

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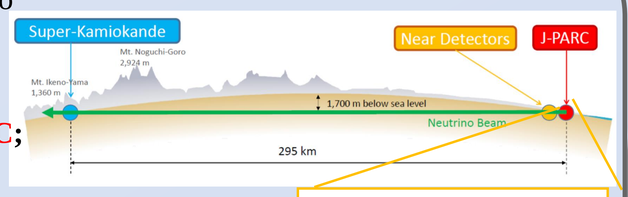
1. T2K Experiment

T2K is a long baseline experiment studying neutrino oscillations in the appearance and disappearance channels **[1]**.

- ν (FHC) or $\bar{\nu}$ (RHC) beam production at **J-PARC**;
- Near detectors – **ND280**, INGRID, WAGASCI;
- 50 kt water Cherenkov detector– Super-Kamiokande.



ND280

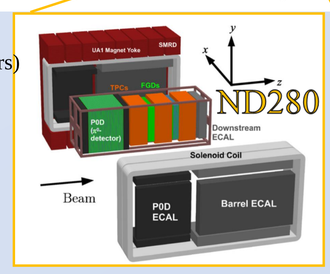
- constrains cross-section and flux models models which allows to obtain more precise measurements of oscillation parameters.
- standalone cross-section measurements.

TPC (Time Projection Chambers)

- Momentum measurement.
- Particle identification (dE/dx measurement).

FGD (Fine Grained Detector)

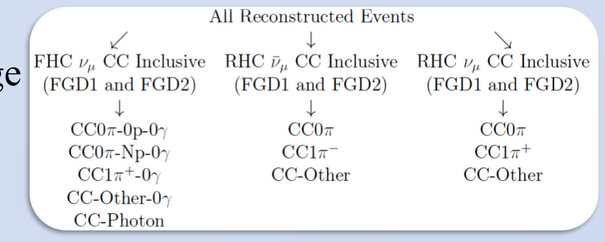
- Target mass.
- Recoil proton detection.
- Contained pion tags.



2.Near Detector Fit

ND280 : fit to parameterized model divided by neutrino type

- CC0π sample contains mostly Charge Current Quasi Elastic interactions (**CCQE**)
- CC1π - Resonant interactions with Pion Production (**RES**)
- CC-Other - Deep Inelastic Scattering (**DIS**).



NEW: inclusion of photon and proton tag

- **Photon tag** increases purity of remaining samples,
- **Proton tag** adds separation of Q^2 phase space. Since there are many physical effects only relevant at low Q^2, such as Pauli blocking, the new samples allow to better probe them.

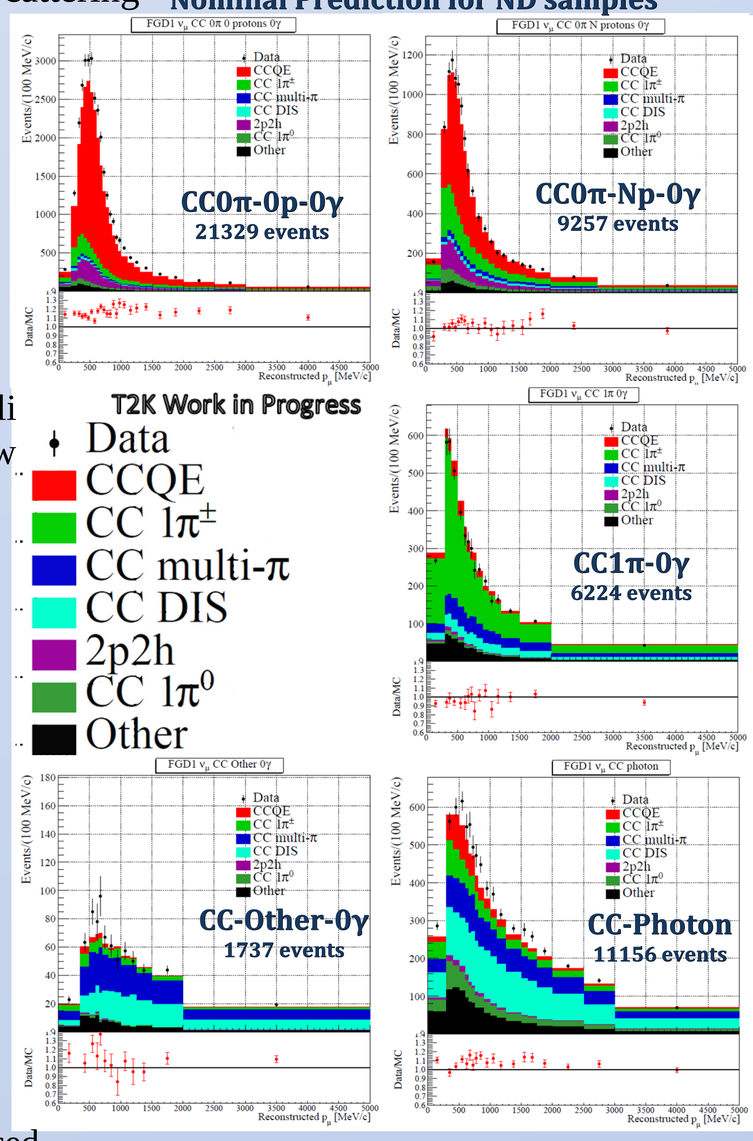
Model consist of 75 cross-section and 100 flux parameters.

Cross-section model improvements, for example:

- nucleon FSI,
- separation of 2p2h into pn/nn
- expanded π kinematic systematic
- Expanded Spectral Function description.

The flux uncertainties are reduced thanks to **new NA61/SHINE replica target data** which reduces flux uncertainties **[2]**.

Muon Momentum Distributions [MeV/c] Nominal Prediction for ND samples



T2K uses two fitters,

- MINUIT based,
- Markov Chain Monte Carlo based and called **MaCh3**.

3.Markov Chain Monte Carlo

Markov Chain Monte Carlo (MCMC) is a N-dimensional directed random walk following regions of high likelihood, meant to explore parameter space. Algorithm for accepting step is shown in Eq. (1), where ***logℒ*** is log-likelihood measuring Data/MC agreement **[3]**.

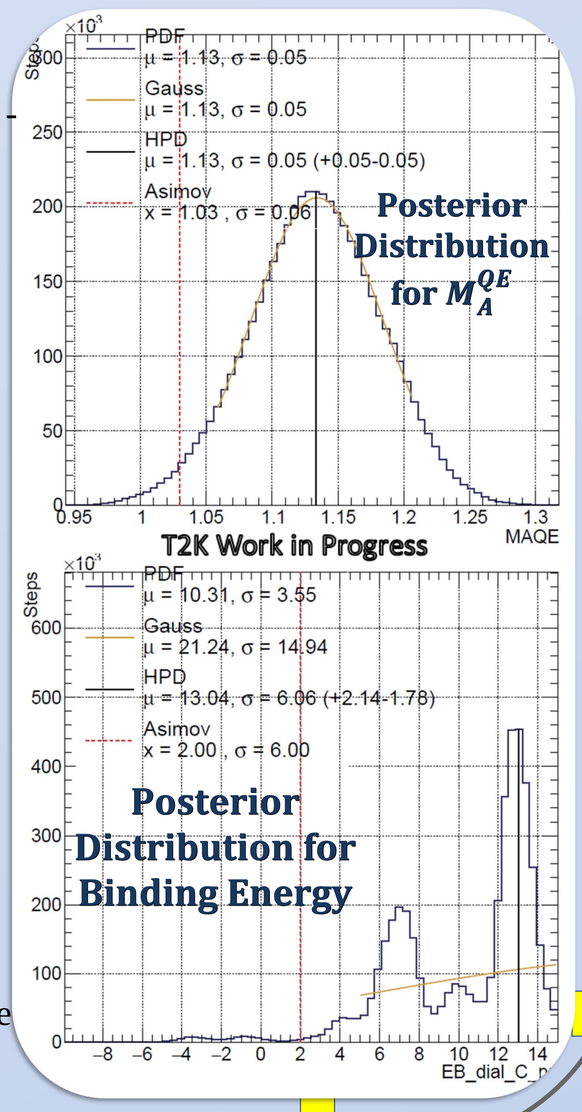
$$A(x', x) = min\left(1, \frac{\mathcal{L}(x')}{\mathcal{L}(x)}\right) = min\left(1, e^{log\mathcal{L}(x) - log\mathcal{L}(x')}\right) \quad (1)$$

- If ***-logℒ*** in proposed step is lower than ***-logℒ*** in a current step, the step is always accepted.
- If ***-logℒ*** in proposed step is greater than in current step, the step might be accepted.

MCMC doesn't find the minimum of ***-logℒ*** , but rather samples the posterior ***-logℒ*** and finds the probability distribution function describing the full model.

Posterior 1D Distribution

- Obtained by marginalizing over N-1 dimensions for each particular systematic parameter.
- Most parameters have Gaussian distributions.
- A big advantage of MCMC is that it can deal with non-Gaussian distribution, which can be consequence of discontinuous likelihoods.



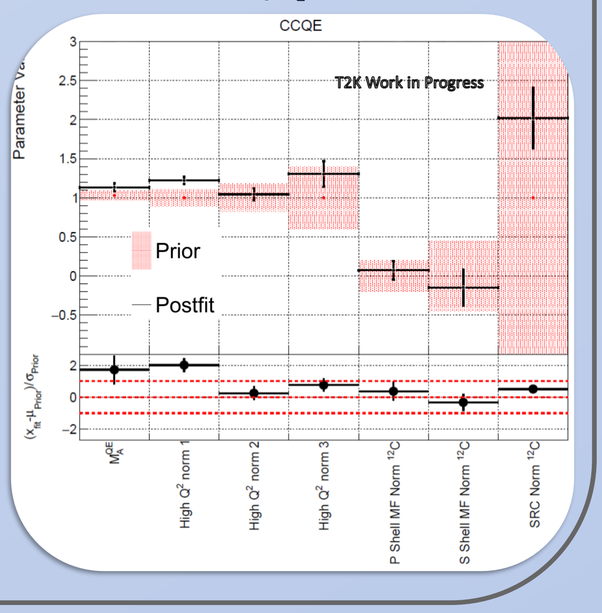
4.Near Detector Results

- High shift of M_A^{QE} is consistent with the previous **T2K** results **[4]**.
- Shift of **High Q^2** parameters indicate that dipole form factor doesn't give enough freedom.
- **P-Shell** and **S-Shell** are in prior error band but with significant error reduction.
- Furthermore, we observe increase of **Short-Range Cor-relation** in Spectral Function model, which is expected considering what electron scattering measurement observed **[4]**.

Based on this we expect not only error reduction but also changes to spectra at FD.

From posterior distributions, extract postfit value for each parameters and compare with prior value and error.

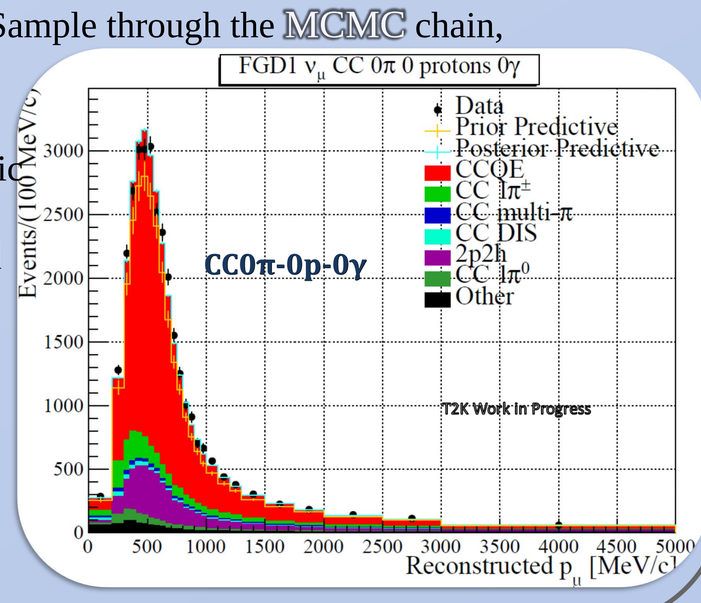
Selected CCQE parameters



5.Posterior Predictive Distributions

- Posterior predictive distribution Sample through the MCMC chain,
- Each sampling corresponds to a set of systematic parameters and provides distributions of kinematic variables.
- The error in each bin is estimated from the spread of toy MC distributions.

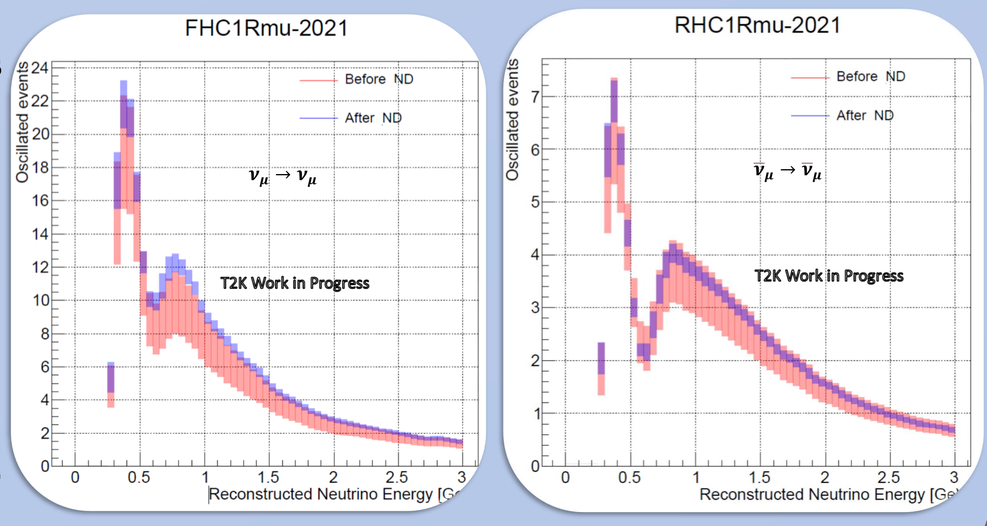
Significant error reduction after ND280 fit and agreement of predictions with the data.



6.Impact on Far Detector

For the final results MCMC fitter is performing **simultaneous fit of near and far** detector samples

However, for validation purposes ND280 fit is also performed. Then posterior predictive spectra at far detector are obtained, which are changed due to parameter shift.



Summary

T2K introduced new samples to ND280 using proton and photon tag. This allowed to expand cross-section systematic model by introducing more robust treatment of Spectral Function.

References
[1] Nucl. Instrum. Meth. A 659 (2011),
[2] Eur.Phys.J. C79 (2019) no.2, 100
[3] Biometrika Vol. 57, No. 1 (Apr., 1970),
[4] Phys. Rev. D 103, 112008 (2021)
[5] J. Phys. G: Nucl. Part. Phys. 16 507

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