Simulated Data Studies for the T2K Experiment Neutrino Oscillation Analysis

Adam Speers

IOP HEPP Conference

09/04/2025

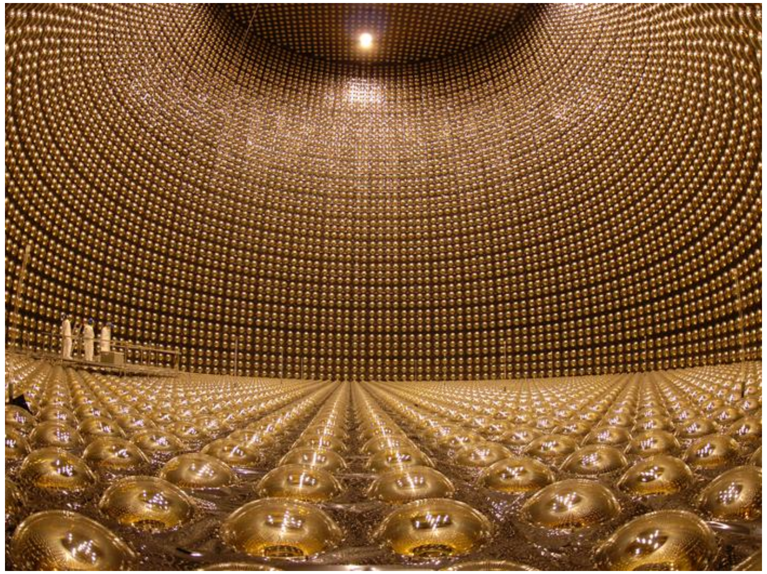
Lancaster University

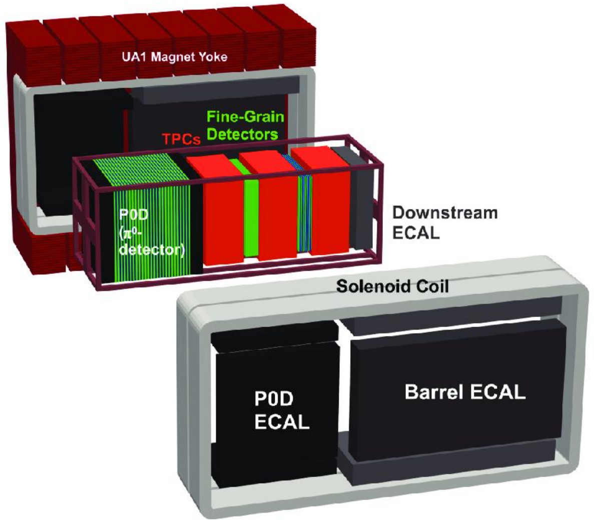
Outline

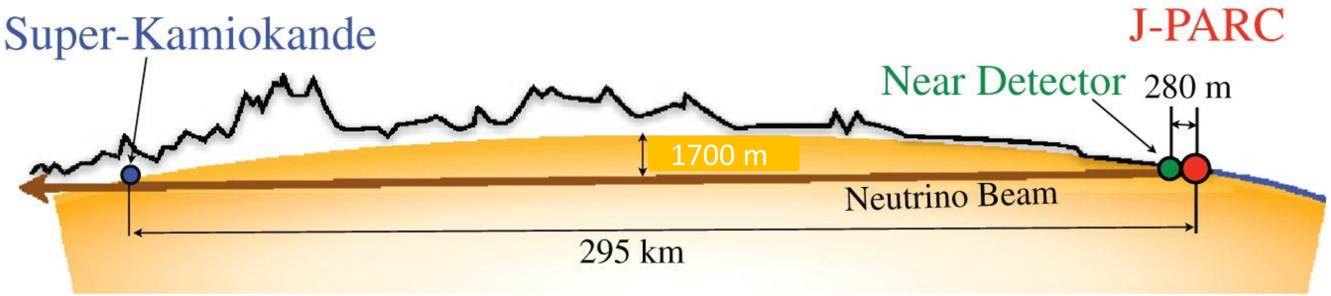
- The T2K Experiment + Near Detector Fit
- What are Simulated Data Studies?
- Simulated Data Studies Performed
- The GUNDAM Fitter
- Fit Analysis
- Further Work

The T2K Experiment

- The T2K (Tokai to Kamiokande) Experiment is a long baseline neutrino oscillation experiment located in Japan
- A muon (anti-)neutrino beam is created at the J-PARC facility, beam composition is measured by the near detector complex (ND280 + INGRID)
- Beam travels 295 km through the Earth's crust to the Super-Kamiokande detector
- Combine data from both detectors to find oscillation parameters

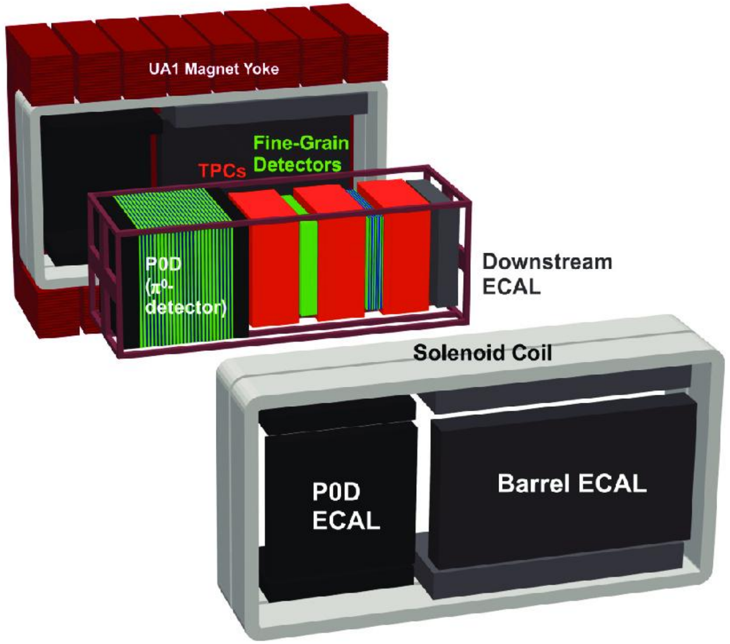


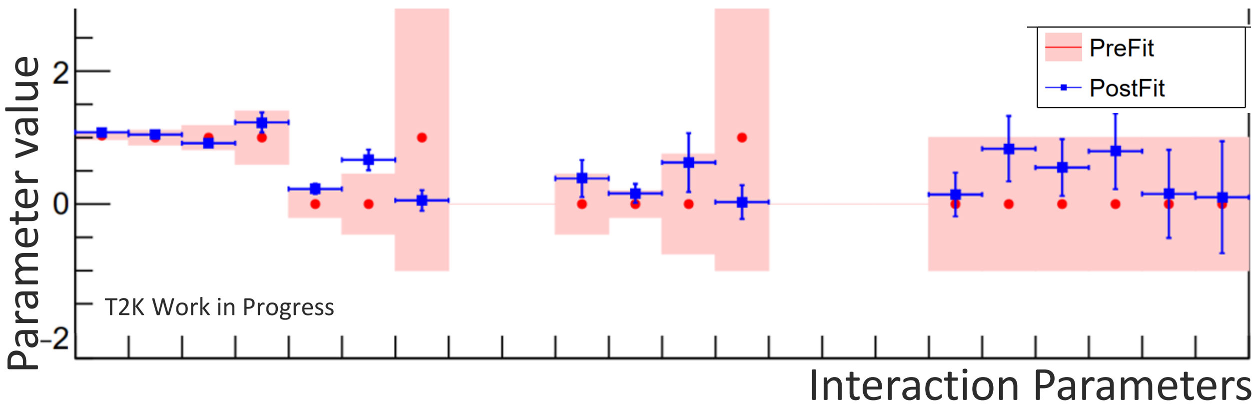




Near Detector Fit

- Want oscillation parameter measurements as accurate as possible
- Parameters estimated from Monte Carlo (MC) models – heavily depend on **beam flux, detector efficiency and neutrino interaction**
- Data from ND280 detector used to constrain models by fitting: adjusting model parameters to bring MC closer to data
- Near Detector fit (ND fit) improves model parameters and reduces systematic uncertainties => **better constraint on oscillation parameters!**

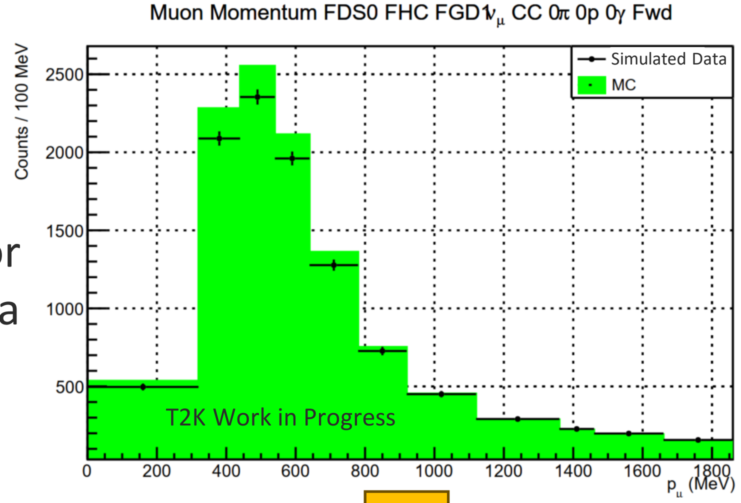




Simulated Data Studies

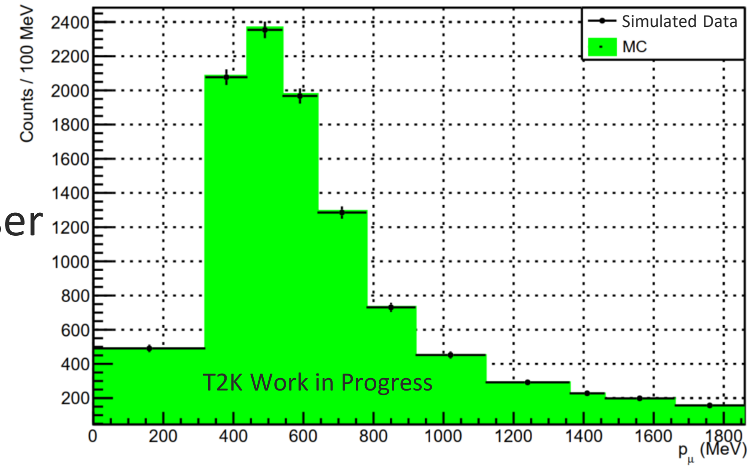
- Simulated data studies (SDS) evaluate biases in the nominal **neutrino interaction model** as used in oscillation analyses
- T2K uses one set of models to run the MC, might other models be more effective?
- Make simulated data by reweighting MC
- GUNDAM fitter used to fit nominal MC to simulated data to analyse bias
- Full analysis requires complete oscillation analysis with SK data, here I am only focusing on ND280

<u>Prefit</u>
Momentum distribution for Simulated data and MC



<u>GUNDAM FITTER</u>

<u>Postfit</u>
MC pulled closer to SD

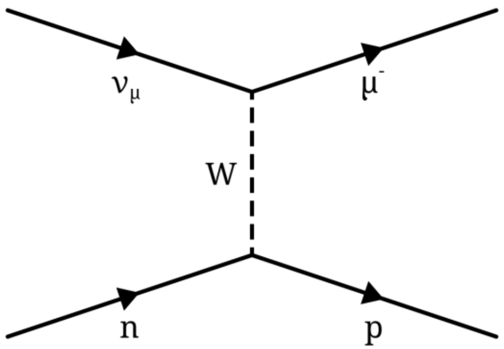


Studies Performed

- 19 total simulated data sets
- Can be grouped by which part of the model is changed:

CCQE Axial Form Factors:

- AXFF Dipole
- AXFF ZExp M1sig
- AXFF ZExp Nom
- AXFF ZExp P1sig
- AXFF 3comp M1sig
- AXFF 3comp Nom
- AXFF 3comp P1sig



Axial form factors are used to model the axial part of the electroweak nucleon form factor for the CCQE (charged-current quasi-elastic) model.

Z-expansion and **3-component** are alternative models, and each model has +/- σ (StDev) predictions in addition to the nominal SDS model

Nuclear Model:

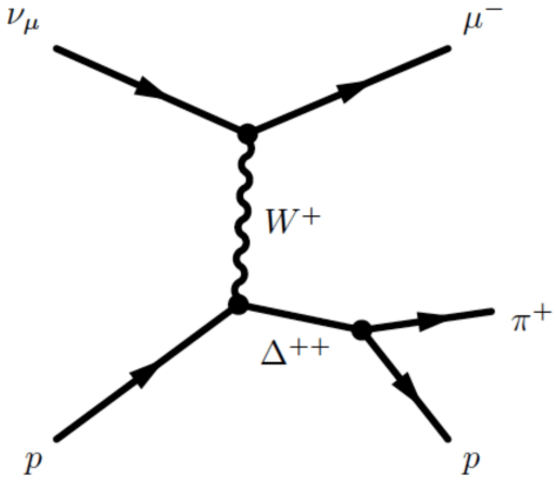
- SF to LFG
- SF to CRPA
- SF to SuSAv2

NEUT's spectral function model is used to model nuclear effects in CCQE neutrino interactions. Here it is reweighted to match **local Fermi gas**, **continuous random phase approximation**, and **SuperScaling Approach v2** models

Studies Performed

Single Pion Production (SPP)

- Low Q2 SPP
- SPP MatrixEl M1sig
- SPP MatrixEl P1sig
- SPPAdversarial
- Martini1pi



Low-Q² suppression model suppresses SPP cross-section at low Q² - based on MINERvA results using GENIE, this FDS is extreme for T2K.
MatrixEl models give a +/- 1 σ variation of the pion kinematics matrix element.
SPPAdversarial uses a data-driven pion kinematics alteration.
Martini1pi uses a new interaction model from Martini et al.

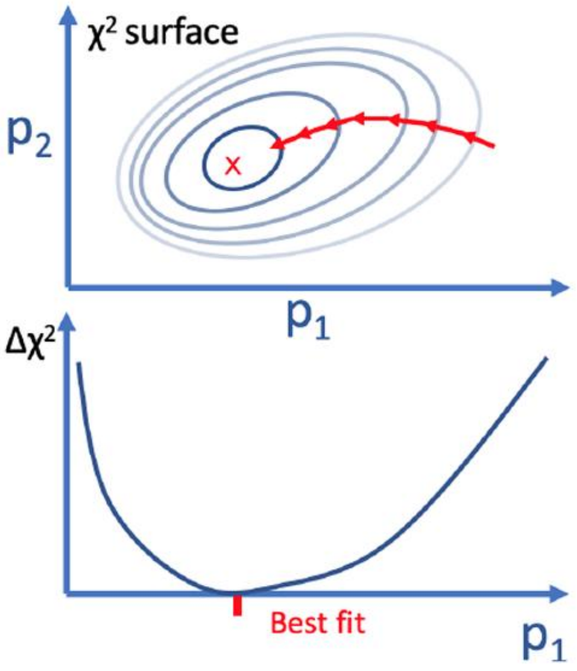
Other:

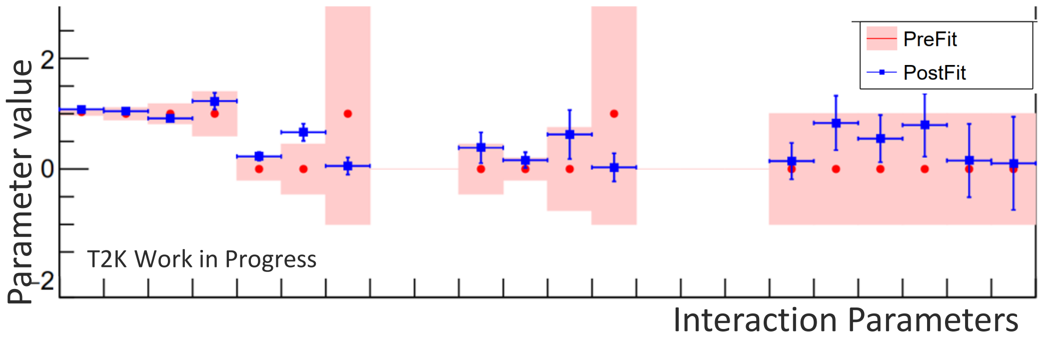
- Non QE
- LQCD Nom
- LQCD M1Sig
- MultiPi Multiplicity

Non-QE reassigns CCQE fit variation to the CC0pi non-QE contributions, to identify inadequacies in non-CCQE interaction models that are being offset by CCQE.
LQCD changes the axial form factor to fit lattice QCD calculations
MultiPi Multiplicity is an alternative model for production of multiple pions

GUNDAM

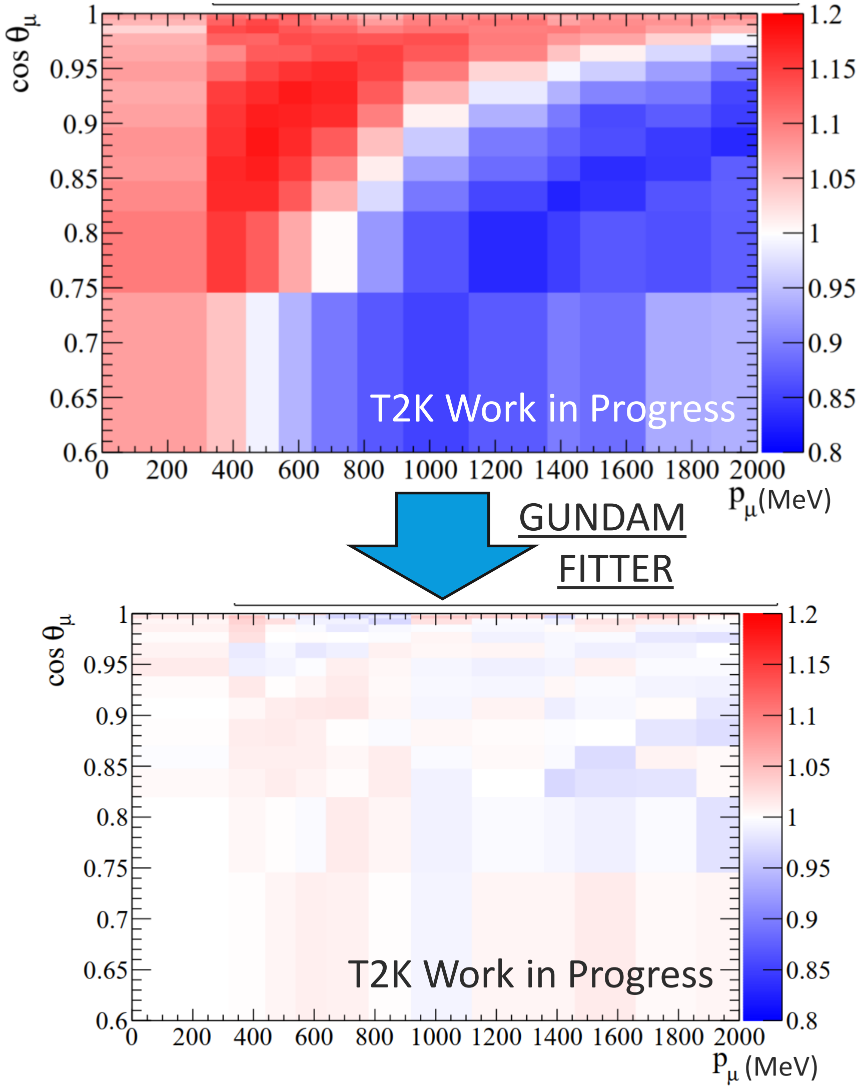
- GUNDAM: Generalized and Unified Neutrino Data Analysis Methods
- Uses a gradient-descent method to fit nominal MC to data by adjusting the MC parameters
- For oscillation analysis, this improves the MC systematic uncertainties by pulling the parameter values closer to Data
- For these simulated data studies, it is used to find the efficacy of fitting the nominal MC to the simulated data





SDS Analysis

- Focusing on the three SDS identified as most important: SF to LFG, Non-QE, SF to CRPA
- 2D Plots: Muon momentum (p_μ) and Muon angular distribution ($\cos\theta_\mu$) presented as ratio nominal MC over SDS
  - White for ratio = 1, red for >1, blue for <1
- Systematics plots: how the nominal MC parameters have been pulled by the fit
  - Focusing on CCQE (Charged-current quasi-elastic) parameters, but many more are not shown here
- Plots compared with results from 2022 oscillation analysis – still expecting similar results despite changes to MC model, reconstruction, ND280 upgrade, etc

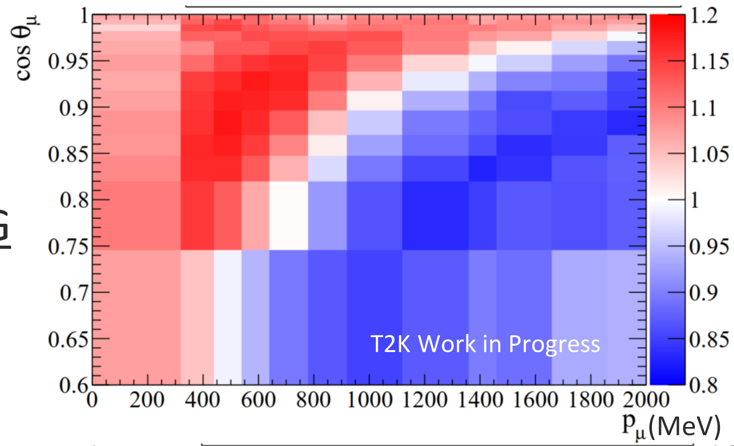


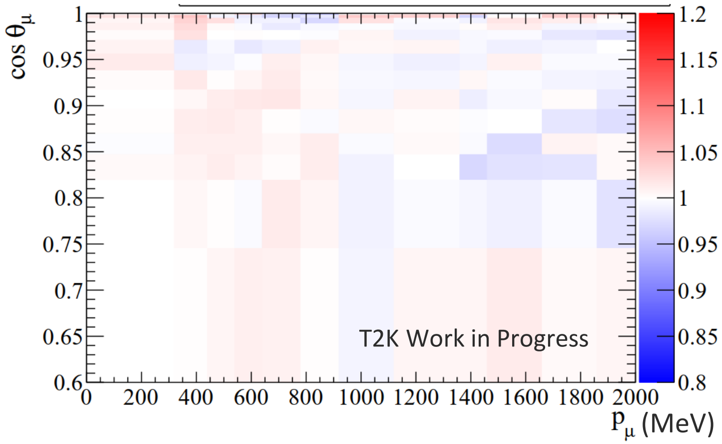
SF to LFG and Non-QE

Sample: Charged-current 0-pion, 0-proton, 0-photon

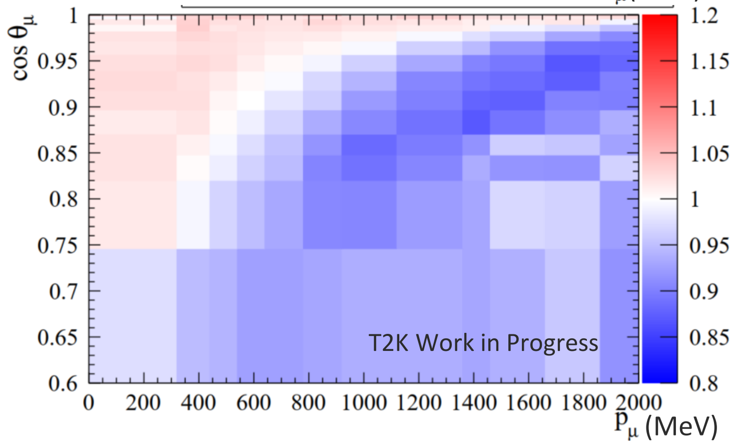
Prefit | Postfit

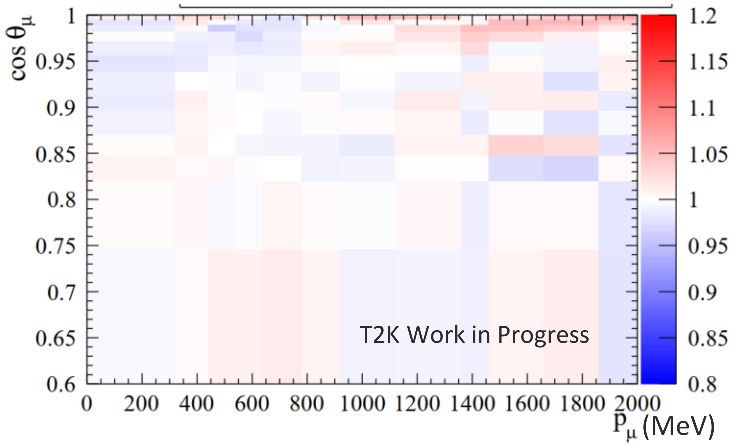
SF to LFG





Non-QE

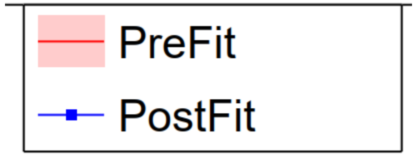




- Angular and momentum distrubtions for Spectral Function to Local Fermi Gas and Non-QE SDS
- Fit has brought nominal MC closer to SDS, as expected

SF to LFG and Non-QE

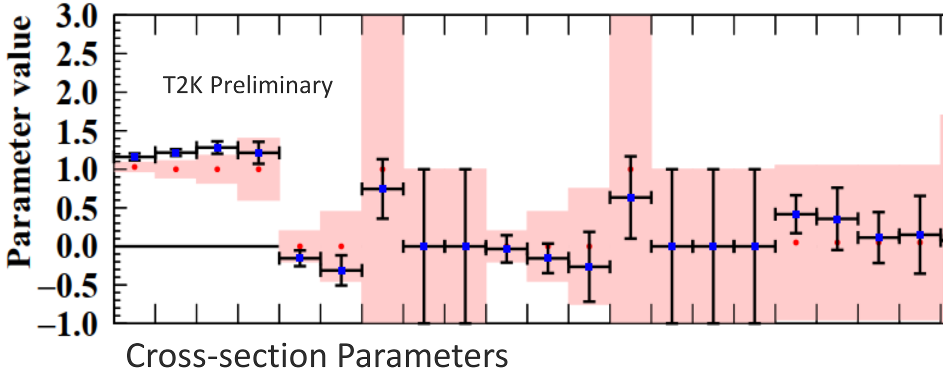
CCQE Cross-Section Parameters

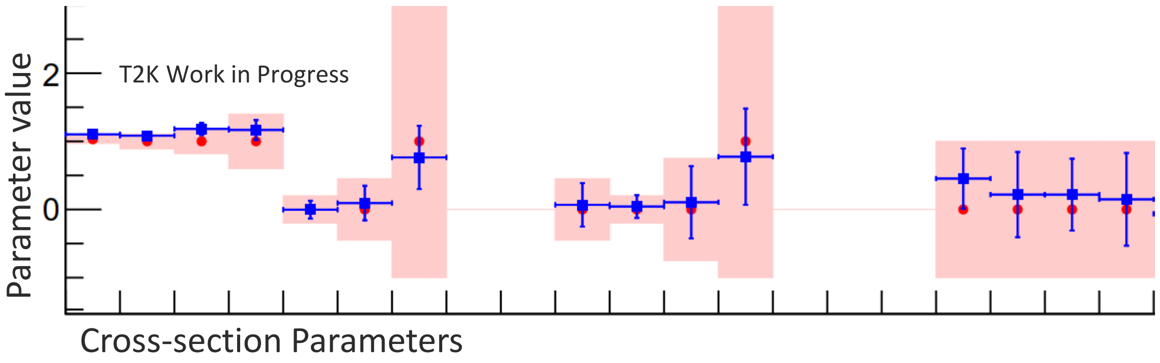


2022 Analysis

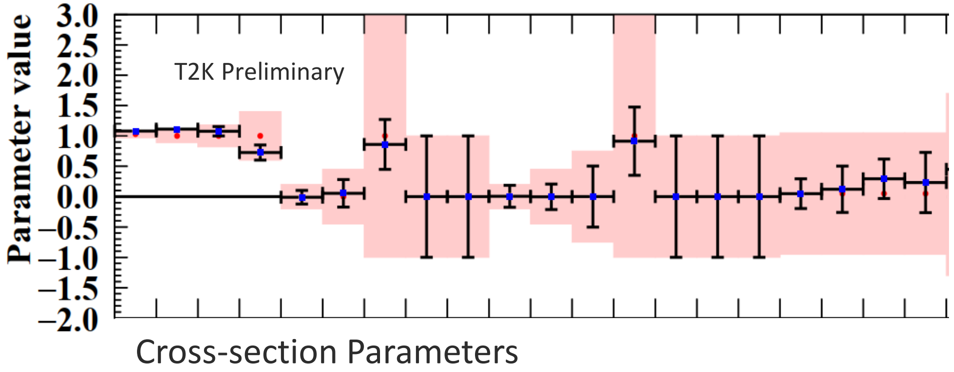
Current

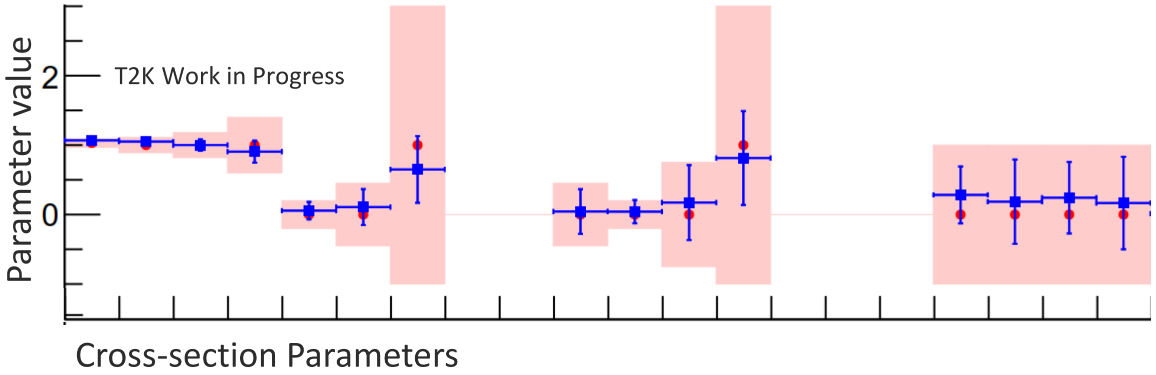
SF to LFG





Non-QE

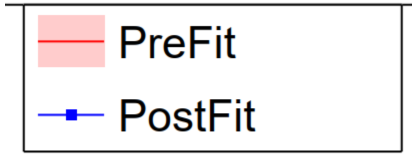




SF to LFG and Non-QE

CCQE Cross-Section Parameters

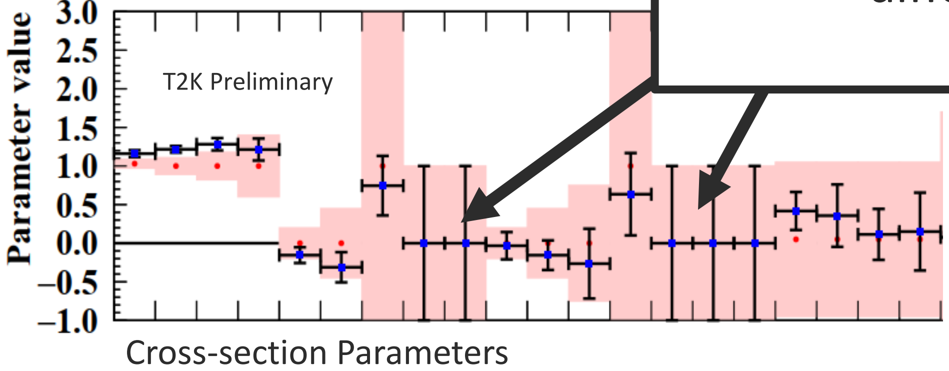
Parameters not fitted in either analysis, just plotted differently

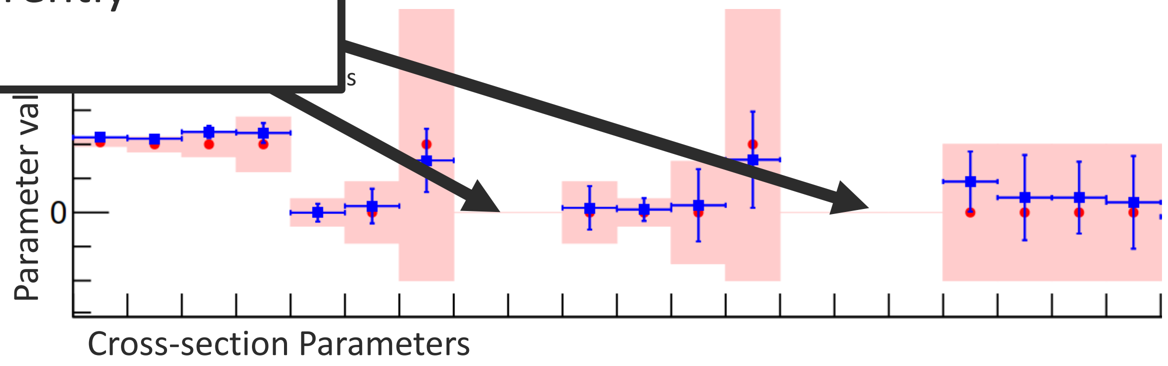


2022 Analysis

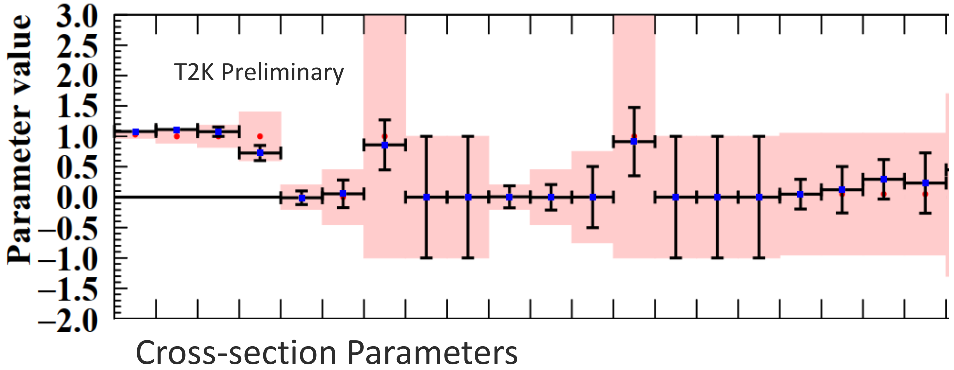
Current

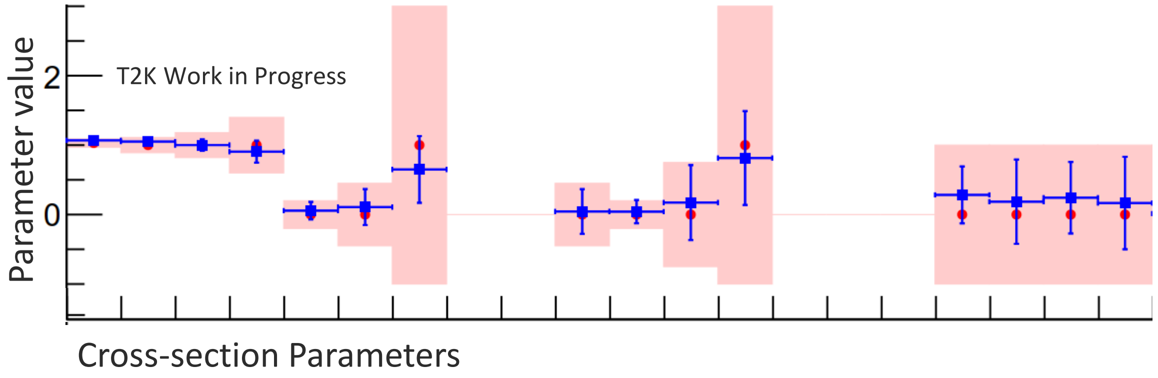
SF to LFG





Non-QE



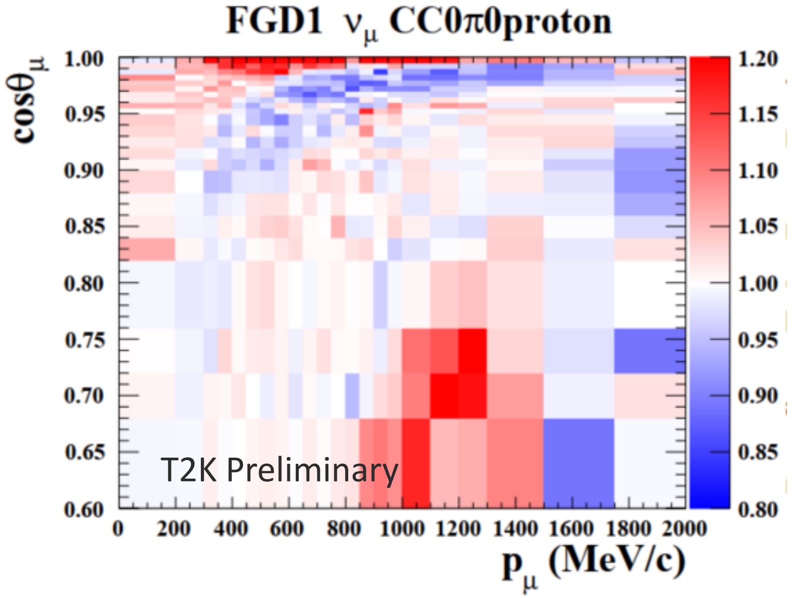


SF to CRPA

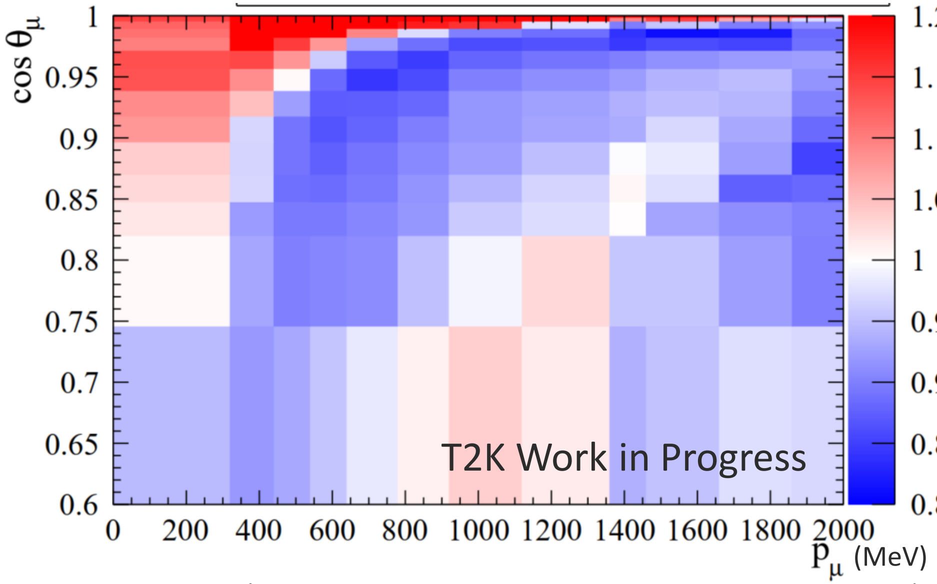
Sample: Charged-current 0-pion, 0-proton, 0-photon

- Postfit does not initially appear quite as good as the previous SDS. Results resemble 2022 analysis distribution (below), but still show some improvement
- Was expecting significant improvement due to additional parameters introduced, so will need to investigate this

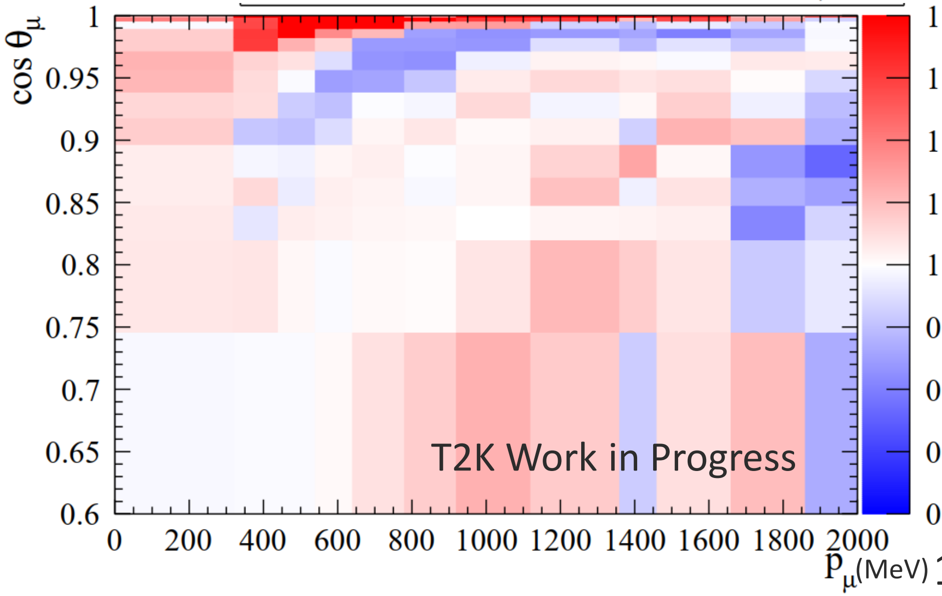
2022 Analysis Sample



Prefit

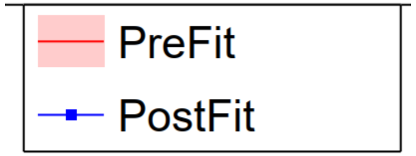


Postfit

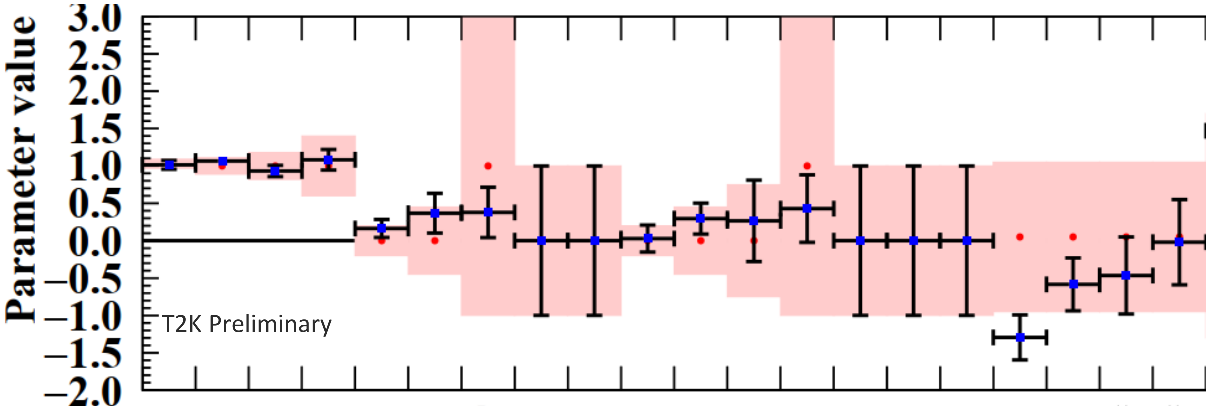


SF to CRPA

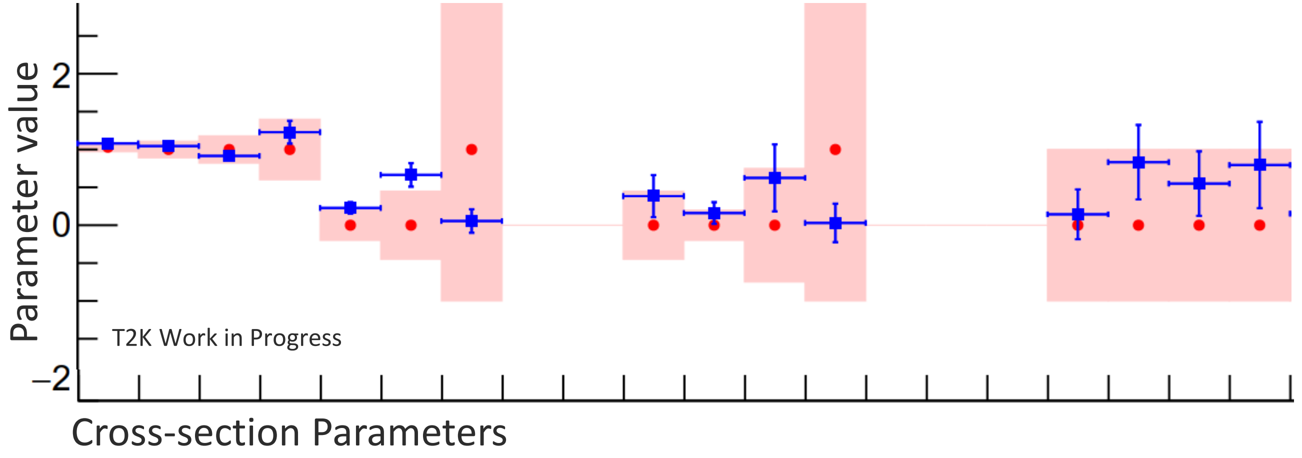
CCQE Cross-Section Parameters



2022 Analysis



Current



- Some parameters show significant difference
- Additional parameters (beyond CCQE cross-section) added since 2022, may explain changes

Conclusions and Future Work

- GUNDAM fits on all 19 SDS complete
- Nominal MC **can be fitted effectively** to SDS using the new GUNDAM fitter
- Comparisons with previous results show similar parameter fits
- Suggests GUNDAM fitter will still effectively fit between significantly different models => choice of model will not significantly affect the overall ND fit

BACKUP

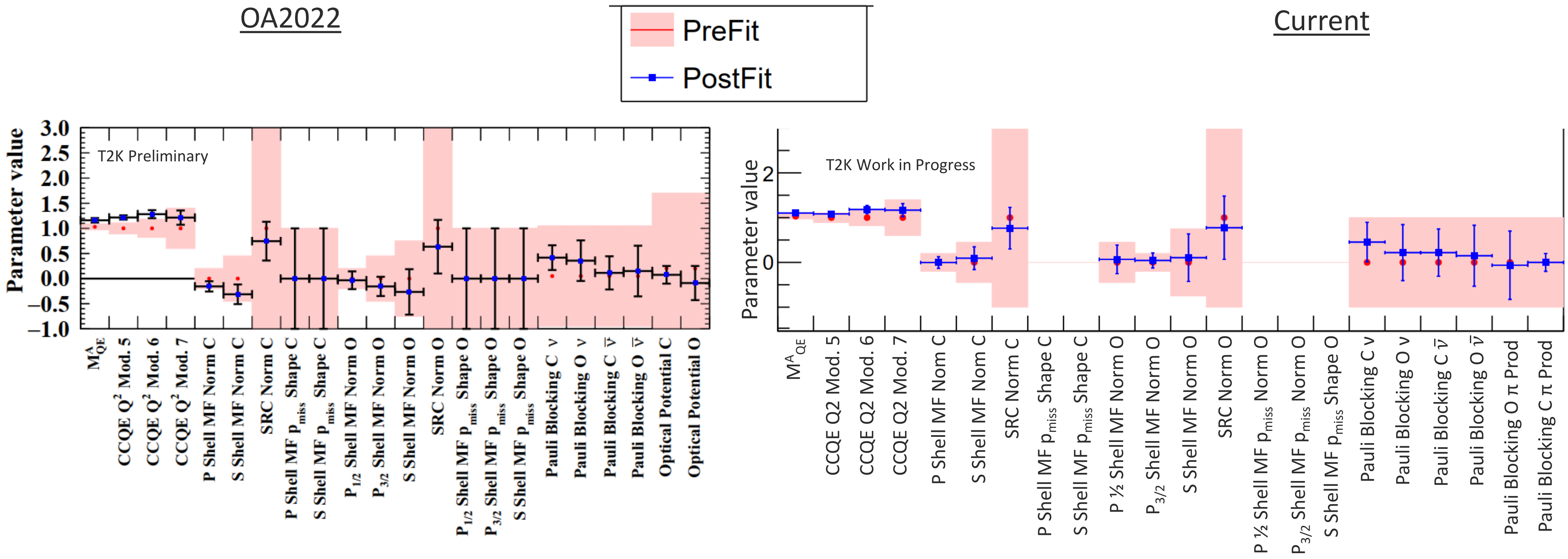
Dial Settings

Fake Data Set	Dial Settings	Fake Data Set	Dial Settings
0 SF to LFG	MAQE=1.21 Eb = 0	10 SF to SuSAv2	MAQE=1.21 Eb = 0
1 non-QE	Default	11 2p2h Eb Correction	Default
2 SPP MatrixEl M1sig	Default	12 SPP Adverserial	Default
3 SPP MatrixEl P1sig	Default	13 RS to Martini	Default
4 SF to CRPA	MAQE=1.21, Eb = 0	14 MultiPi Multiplicity	Default
		15 Low Q2 SPP	Default
5 AXFF ZExp M1sig	MAQE=1.21	16 AXFF 3comp M1sig	MAQE=1.21
6 AXFF ZExp Nom	MAQE=1.21	17 AXFF 3comp Nom	MAQE=1.21
7 AXFF ZExp P1sig	MAQE=1.21	18 AXFF 3comp P1sig	MAQE=1.21
8 LQCD Nom	MAQE=1.21		
9 LQCD M1Sig	MAQE=1.21		

- Certain fake data sets need direct adjustment to dials
- MAQE is the axial mass for quasi-elastic interactions. Automatically set to 1.03, but certain FDS need historical value of 1.21
- Eb - nuclear binding energy. Typically has a value of 2-4 MeV, but set to 0 for FDS that affect the nuclear model

SF to LFG

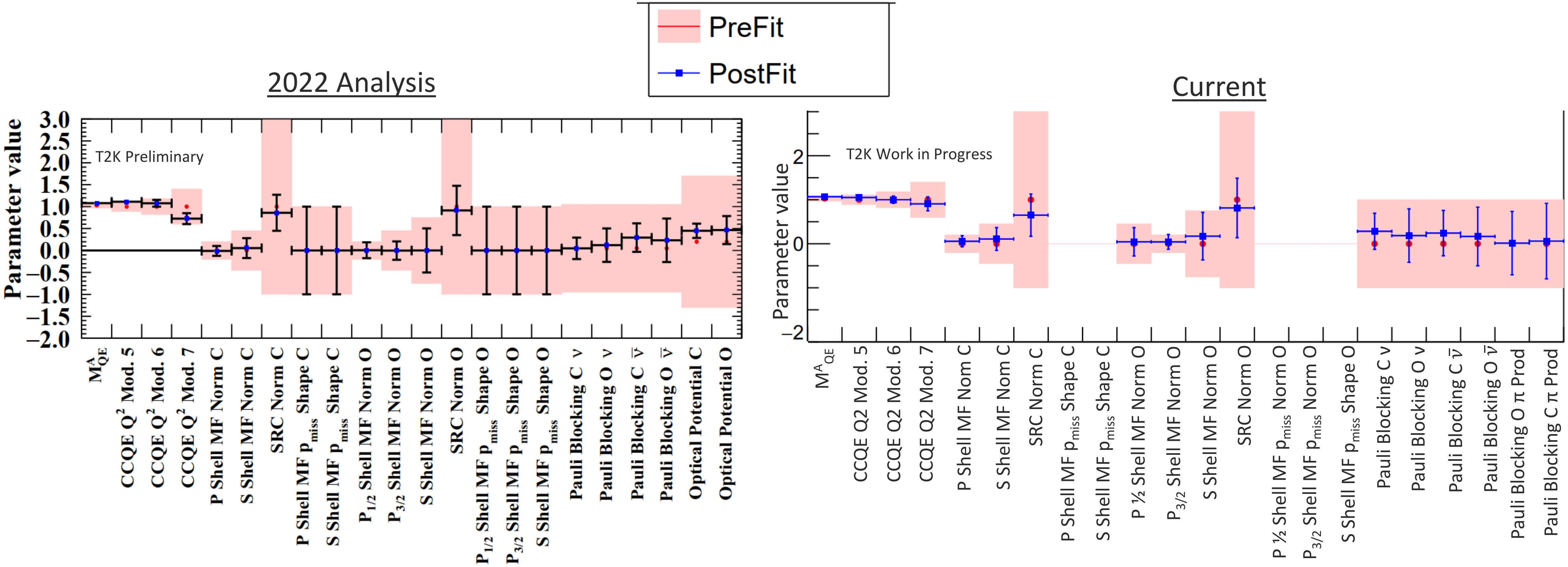
CCQE Cross-Section Systematics



Blank fields are not included in the fit

Non-QE

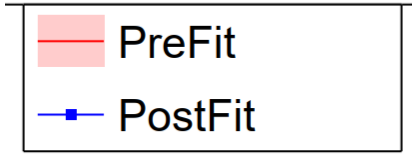
CCQE Cross-Section Systematics



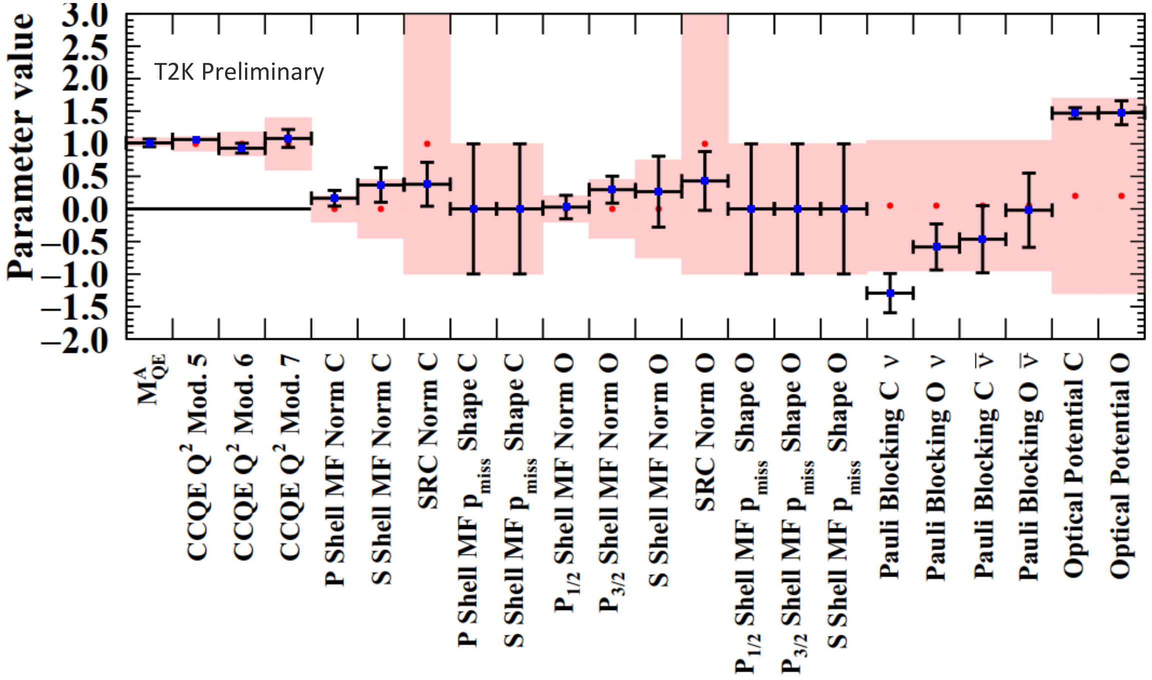
Blank fields are not included in the fit

SF to CRPA

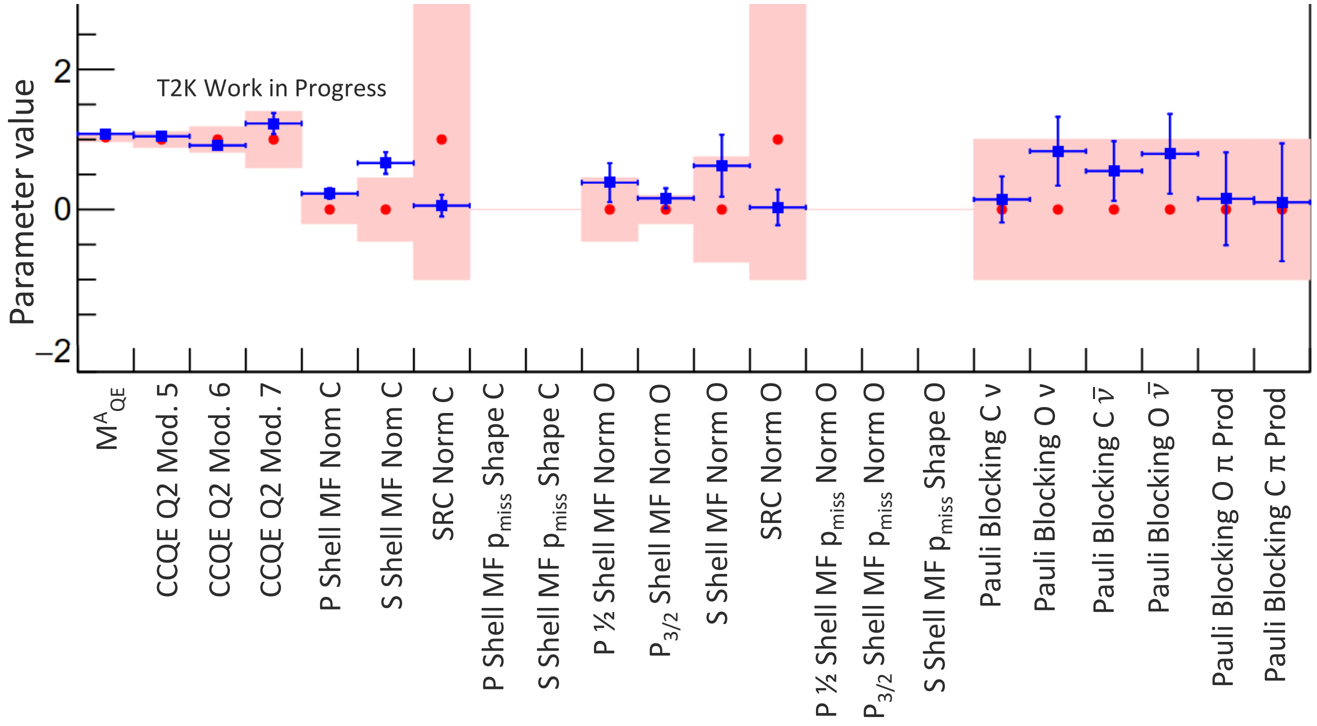
CCQE Cross-Section Systematics



2022 Analysis



Current



Blank fields are not included in the fit