Impact of cross-section uncertainties in the T2K oscillation analyses

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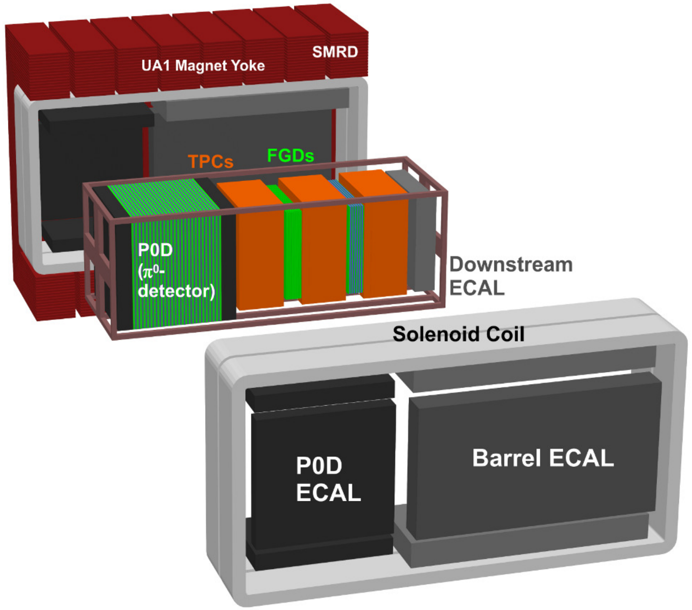
The T2K Experiment

- Long-baseline neutrino oscillation experiment.
- Uses Super-K as far detector at 295 km, 2.5° off-axis.
  - 50 kt Water Cherenkov - oxygen as main target.
- Two purpose built near-detectors, ND280 off-axis and INGRID on-axis.
- Beam energy peaks at around 0.6 GeV.

The ND280

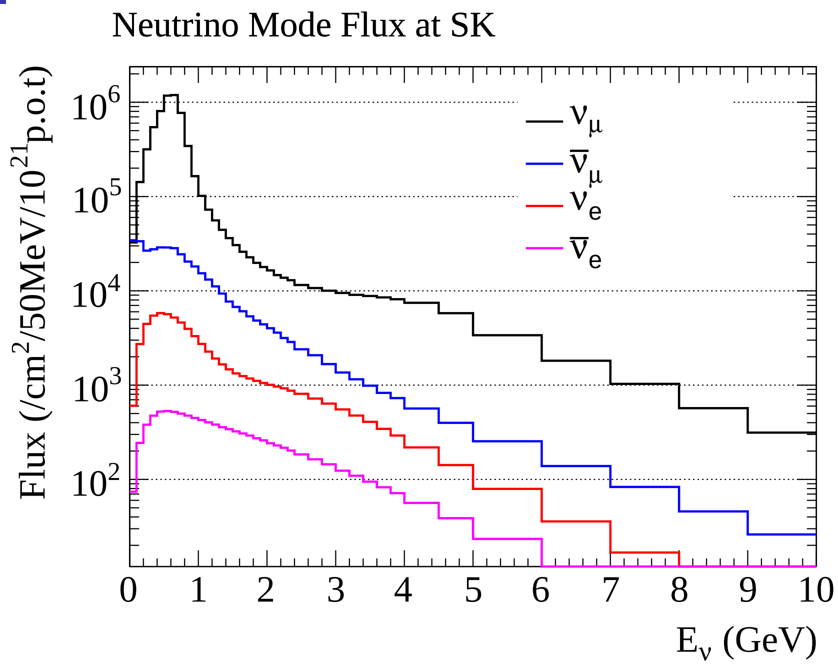


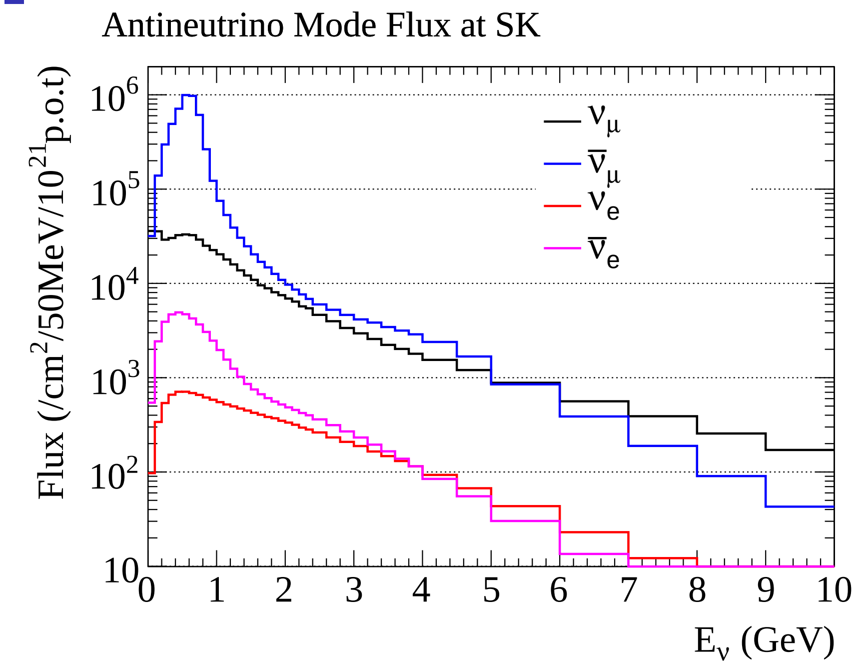
- Magnetised off-axis near detector at 280 m.
- Made up of several complementary subsystems.
- Constrains flux and interaction uncertainties for the oscillation analysis.
- Also used to measure cross sections of neutrino interactions on several different targets.

ND280 Subsystems

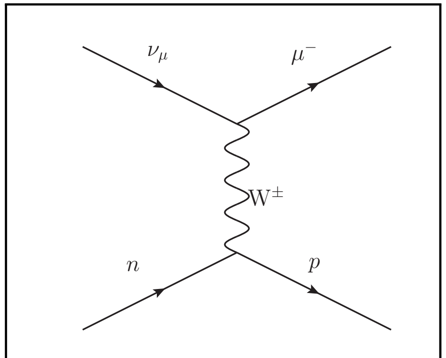
- **P0D** - π^0 Detector
  - Contains brass and lead targets with scintillator.
  - Optionally contains a water target.
- Tracker consists of alternating gaseous argon **TPC**s (time projection chambers) and **FGD**s (fine-grained detectors).
  - **FGD1**, upstream, is entirely scintillator (carbon as nuclear target).
  - **FGD2**, further downstream, has active scintillator and passive water targets.
- Surrounded by lead-scintillator **ECal**s (Electromagnetic Calorimeters).
- Encased in dipole magnet (recycled from the UA1 experiment), which has the **SMRD** (Side Muon Range Detector) attached to the yoke.
- FGD1 (carbon) and FGD2 (carbon/oxygen) are main targets for oscillation fit constraints.

Neutrino Flux at Super-K

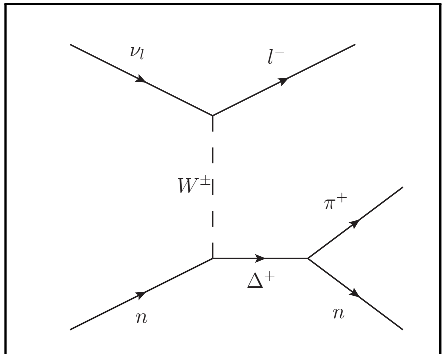




- Flux peak (~ 0.6 GeV) is in the region where CCQE and Resonance are most significant cross sections.
- And any multi-nucleon effects.

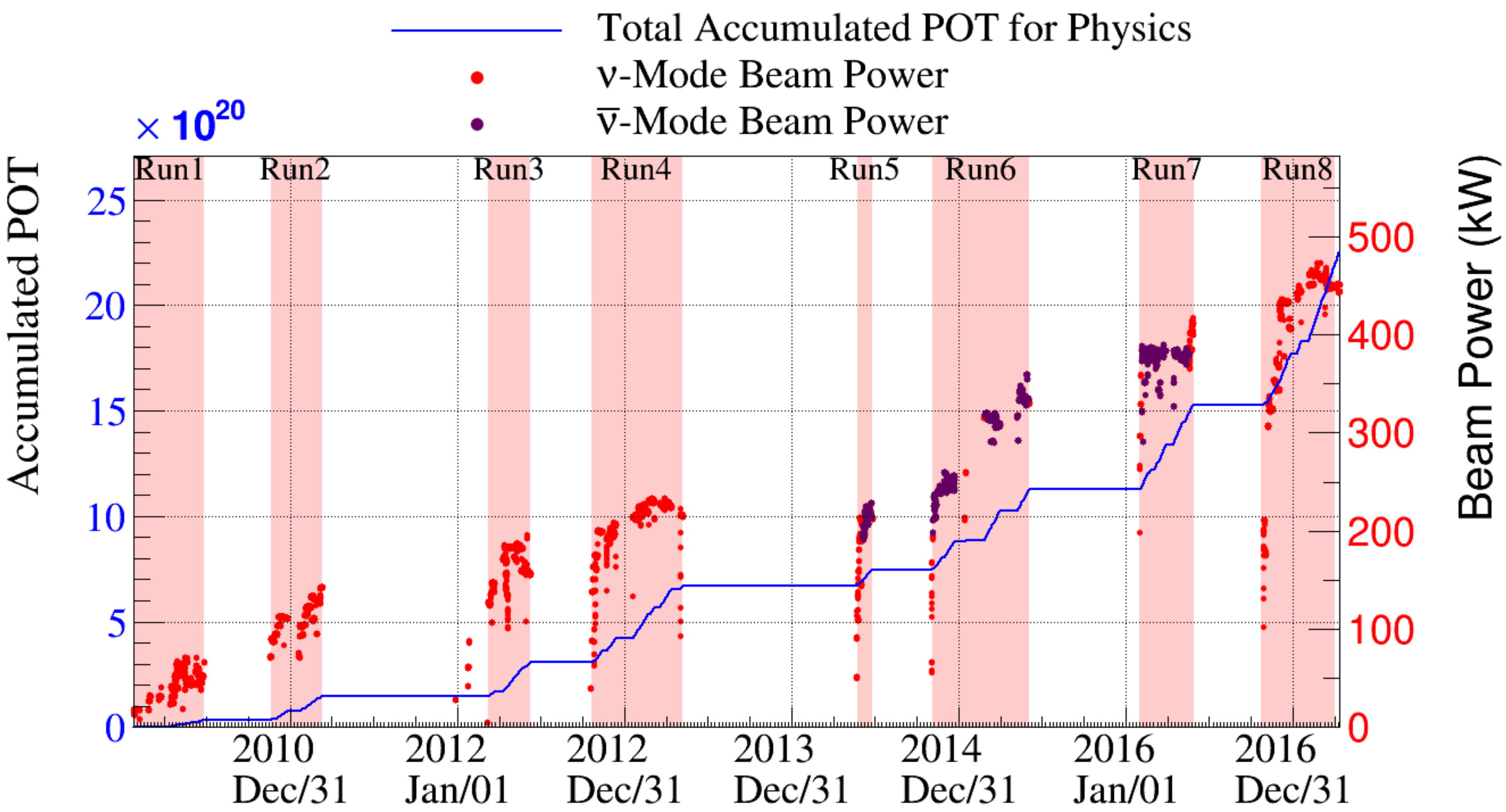


CCQE



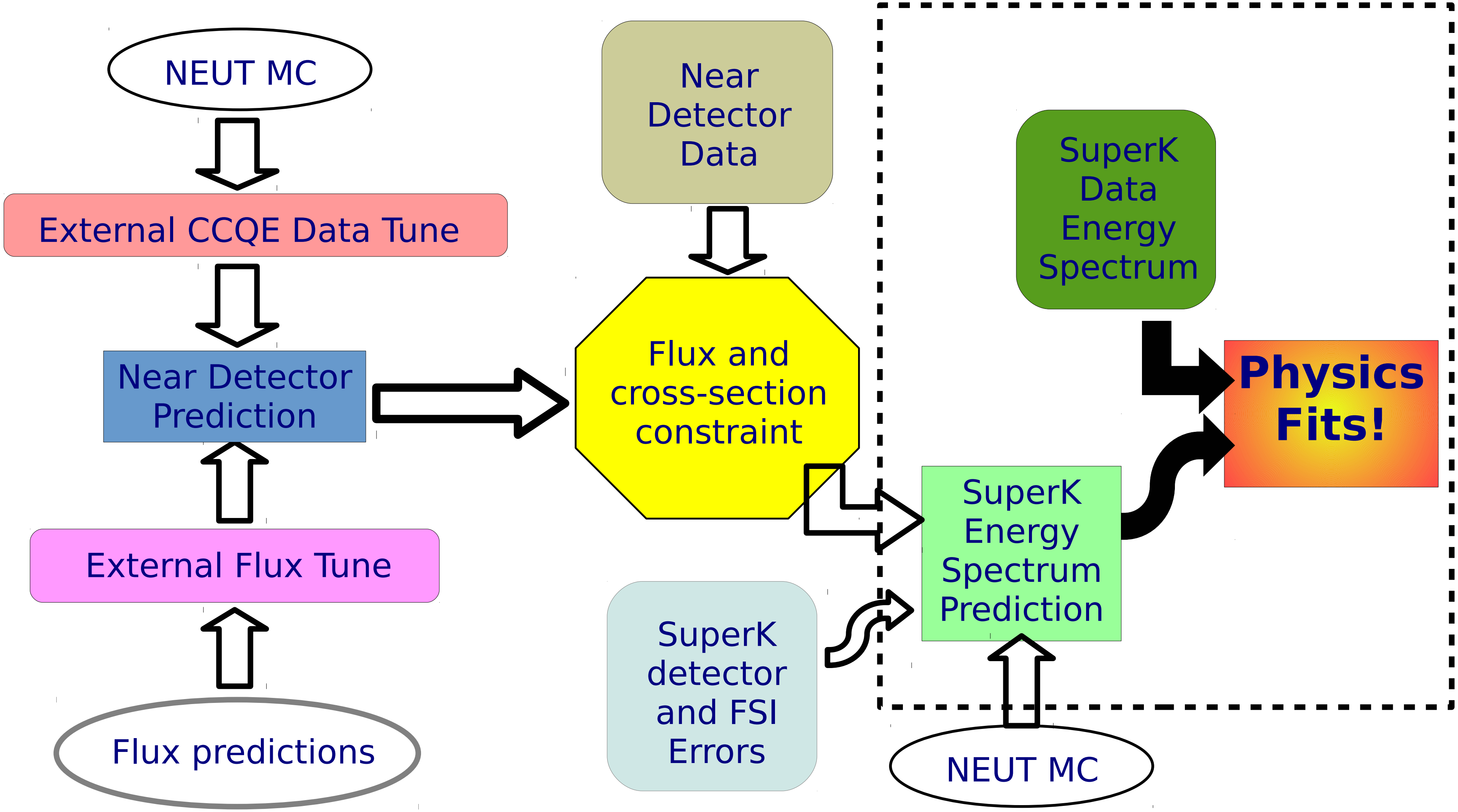
RES

T2K Accumulated Protons on Target



The information in this talk is based on T2K Run1-6.

The T2K Analysis Approach



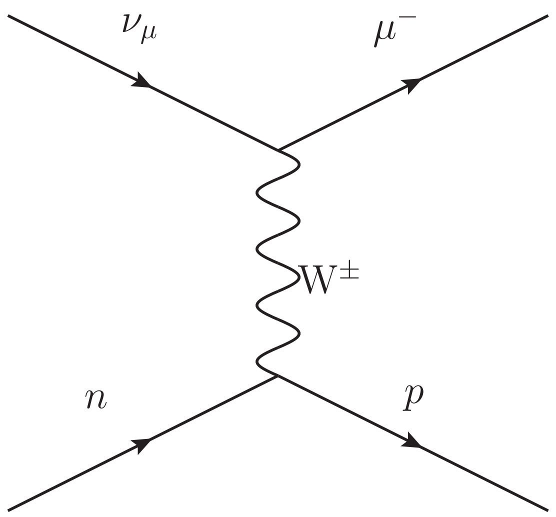
The Interaction Model

- 2016 T2K analysis done using NEUT 5.3.3.
- Using 26 systematic parameters, using fundamental model parameters where possible.
- Five for 1p1h (one-particle, one-hole).
- Three for 2p2h (two-particle, two-hole).
- Three for resonant single pion production.
- Seven for CC coherent, CC Deep Inelastic Scattering and neutral currents.
- One each for ν_e/ν_μ and $\overline{\nu_e}/\overline{\nu_\mu}$.
- Six for Final State Interactions (FSI).

The Interaction Model - 1p1h

- **1p1h** - the neutrino knocks out a single nucleon, as in CCQE.
- M_A^{QE} is the only nucleon-level uncertainty.
- Using the Relativistic Fermi Gas nuclear model.
  - With individual Fermi Momentum and Binding energy parameters for carbon and oxygen.
  - Main near detector target is carbon, main far detector target is oxygen.
- Apply fixed Random Phase Approximation (RPA) effect.

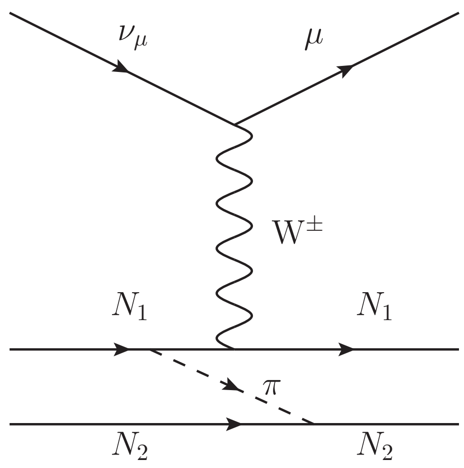
Eg:



The Interaction Model - 2p2h

- Uses the Nieves 2p2h model in NEUT (Nieves et al PRC 83, 045501, 2011).
- Apply normalisation uncertainty parameter for each of carbon and oxygen, applied equally to ν and $\bar{\nu}$.
  - Main ND target is carbon, but also contains some oxygen.
  - Main FD target is oxygen.
- Additional uncertainty on $\bar{\nu}$ to ν ratio.
  - 2017 analyses will have shape uncertainty on 2p2h.
- Often referred to as **MEC** (Meson Exchange Currents), the major contribution of this type of interaction in our models.

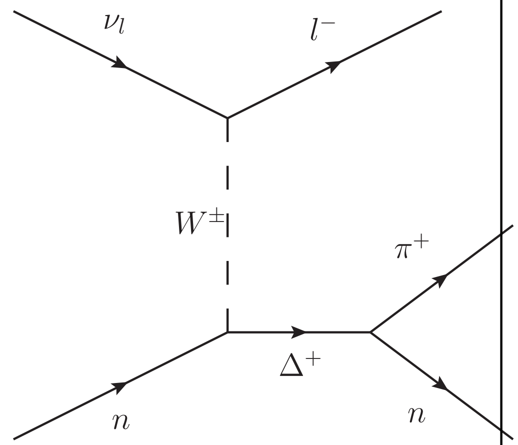
Eg:



The Interaction Model - Resonance

- Uses the Rein-Sehgal model in NEUT. (Rein and Sehgal, Annals Phys. 133, 79, 1981).
- Two uncertainties on nucleon form factors:
  - M_A^{RES}
  - C_5^A
- Uncertainty on non-resonant pion production contribution.

Eg:

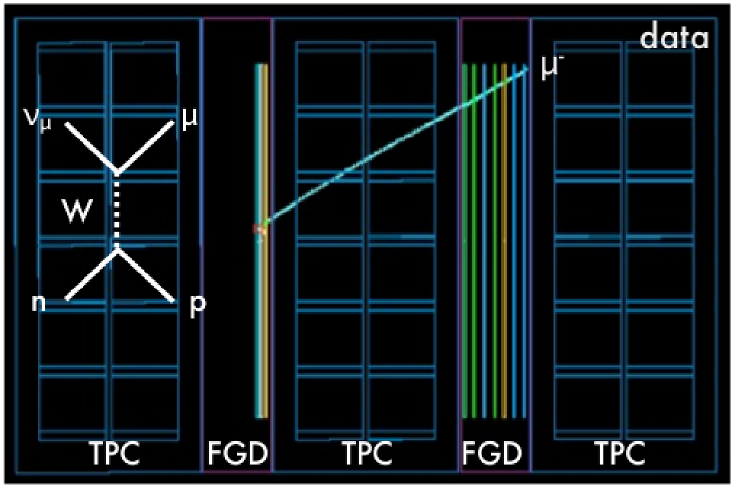


The ND280 Data Fit for Oscillations

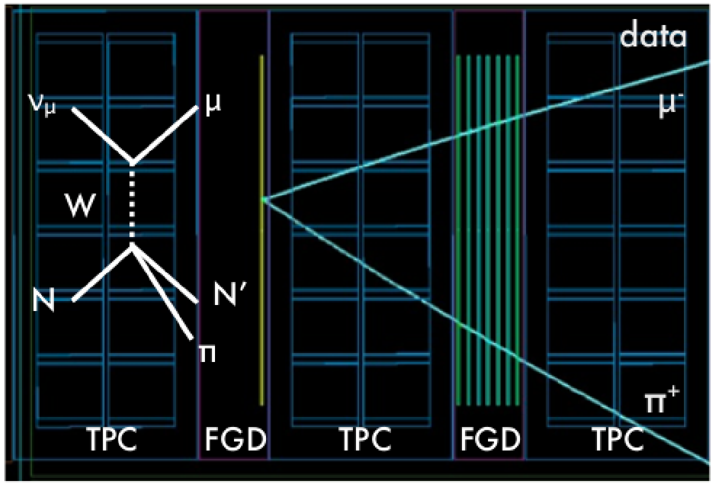
- Fits three topologies in neutrino beam-mode:
  - CC0π, CC1π^+ and CC other.
- Four topologies in antineutrino beam-mode:
  - $\overline{\nu_\mu}$ CC 1-track and $\overline{\nu_\mu}$ CC N-track.
  - ν_μ CC 1-track and ν_μ CC N-track (wrong-sign).
- Fitting multiple samples allows us to maximise sensitivity to different interaction physics.
- Primary target is the more upstream fine-grained detector (FGD1), with carbon target.
- Now also fit samples from FGD2, which contains an oxygen (water) target.
- Events are fitted in bins of muon momentum and angle.

ND280 ν-mode example events (FGD1).

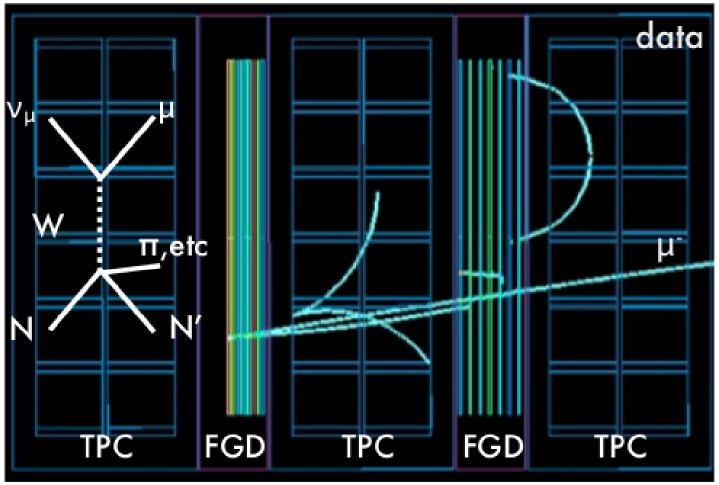
ν_μ CC0π



ν_μ CC1π^+

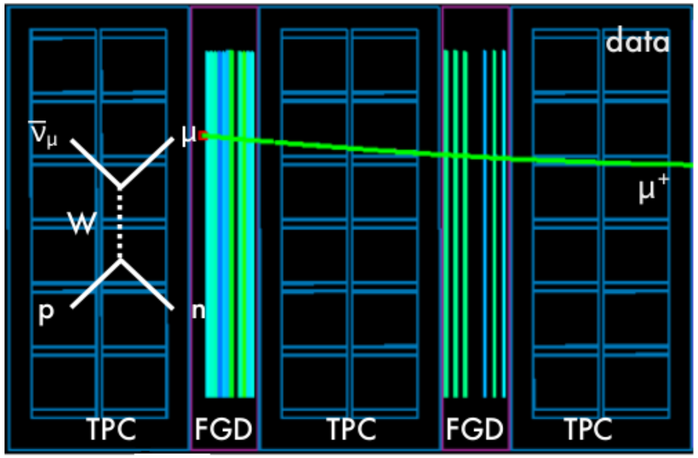


ν_μ CC other

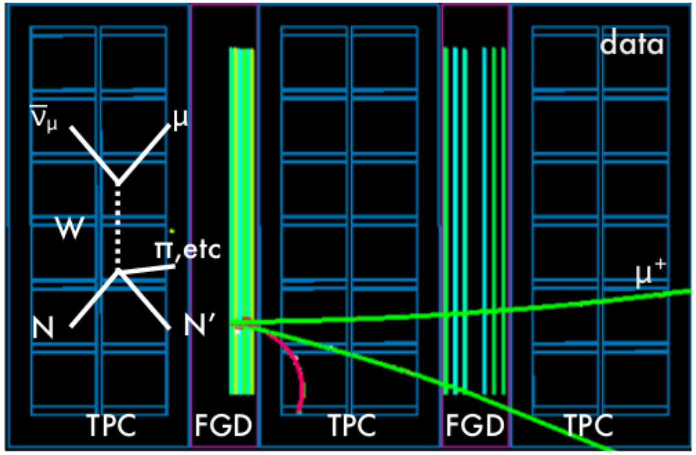


ND280 $\bar{\nu}$-mode example events (FGD1).

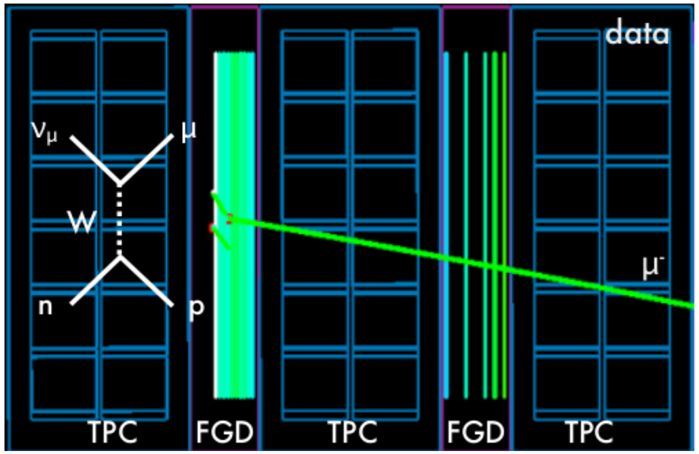
$\overline{\nu_\mu}$ CC 1-track



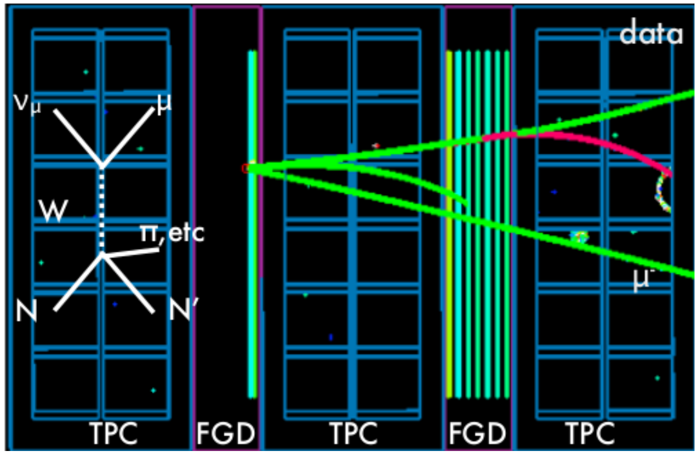
$\overline{\nu_\mu}$ CC N-track



ν_μ CC 1-track (wrong-sign)



ν_μ CC N-track (wrong-sign)



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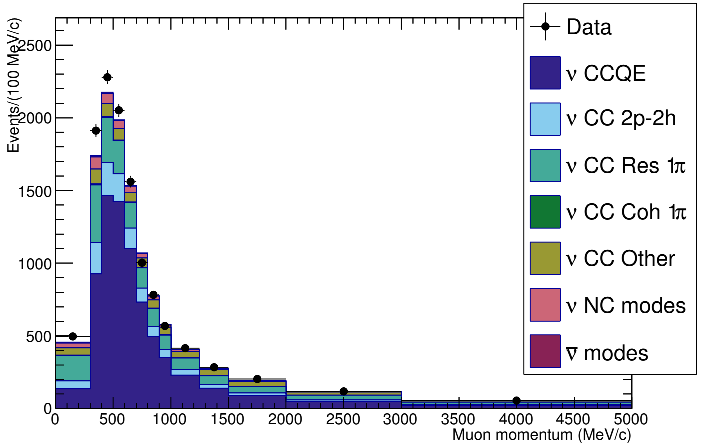
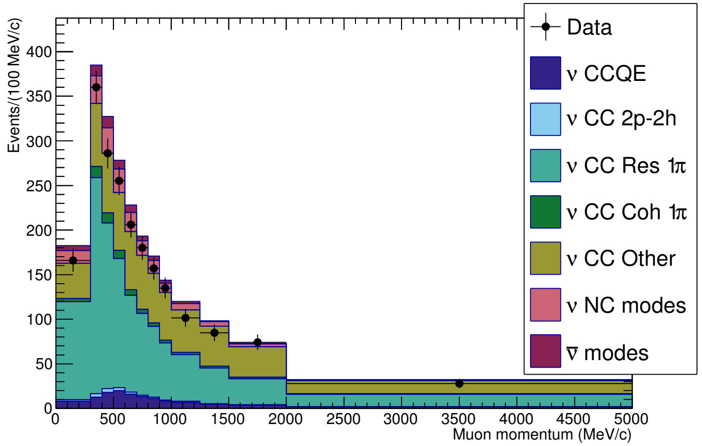
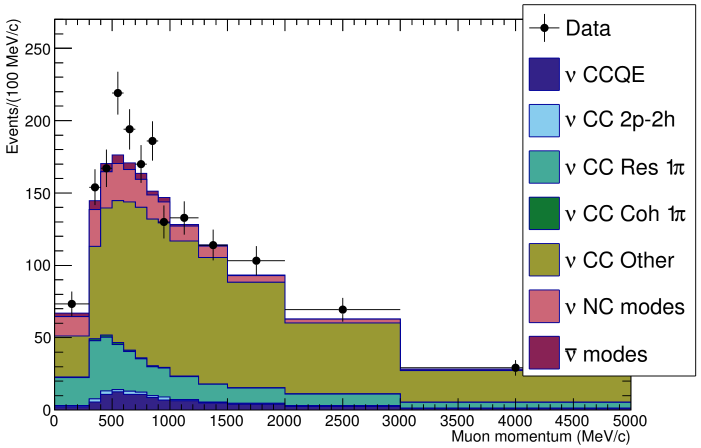
ND280 ν-mode pre-fit spectra (FGD1)



CC0π



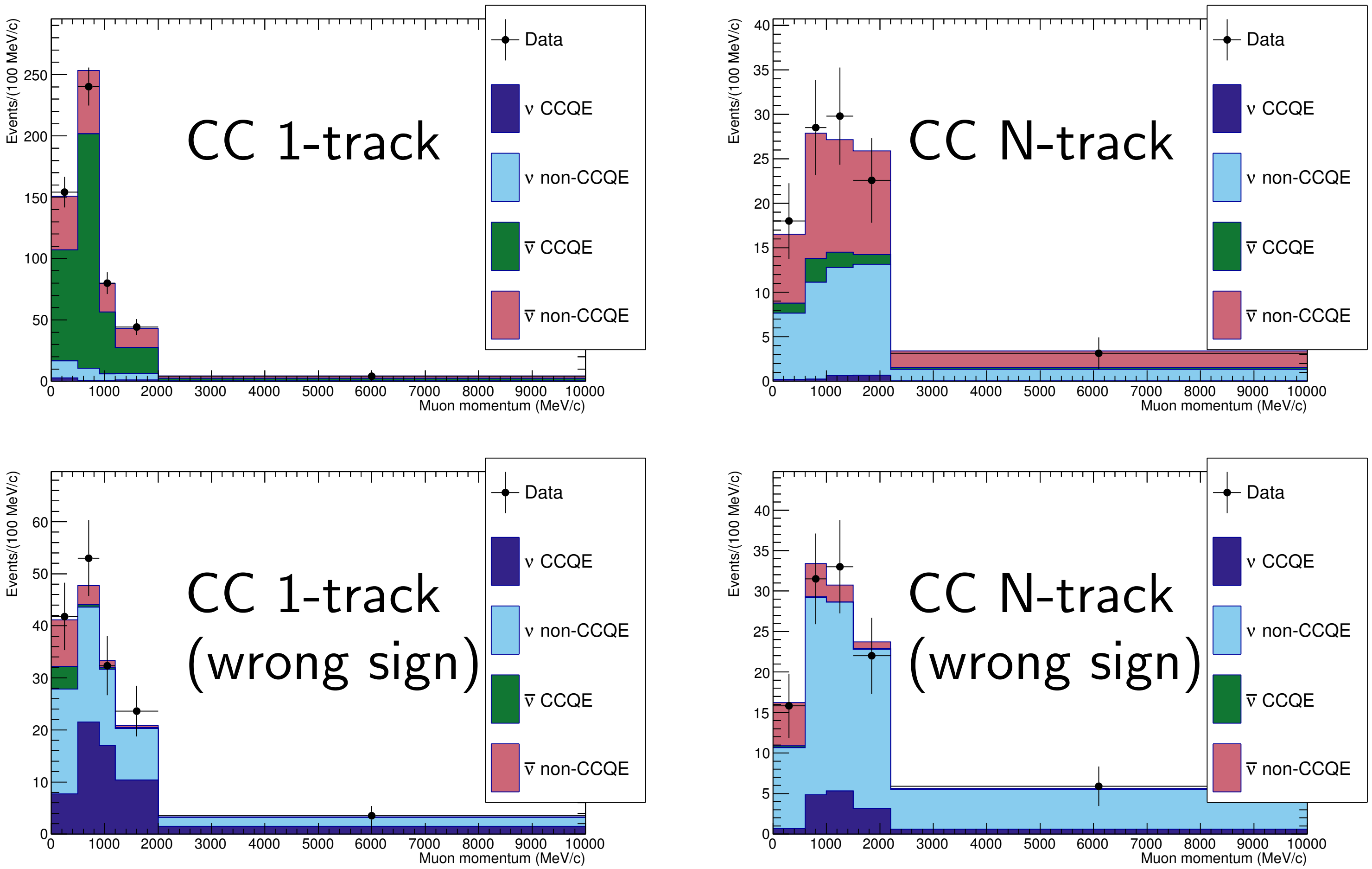
CC1π



CC other

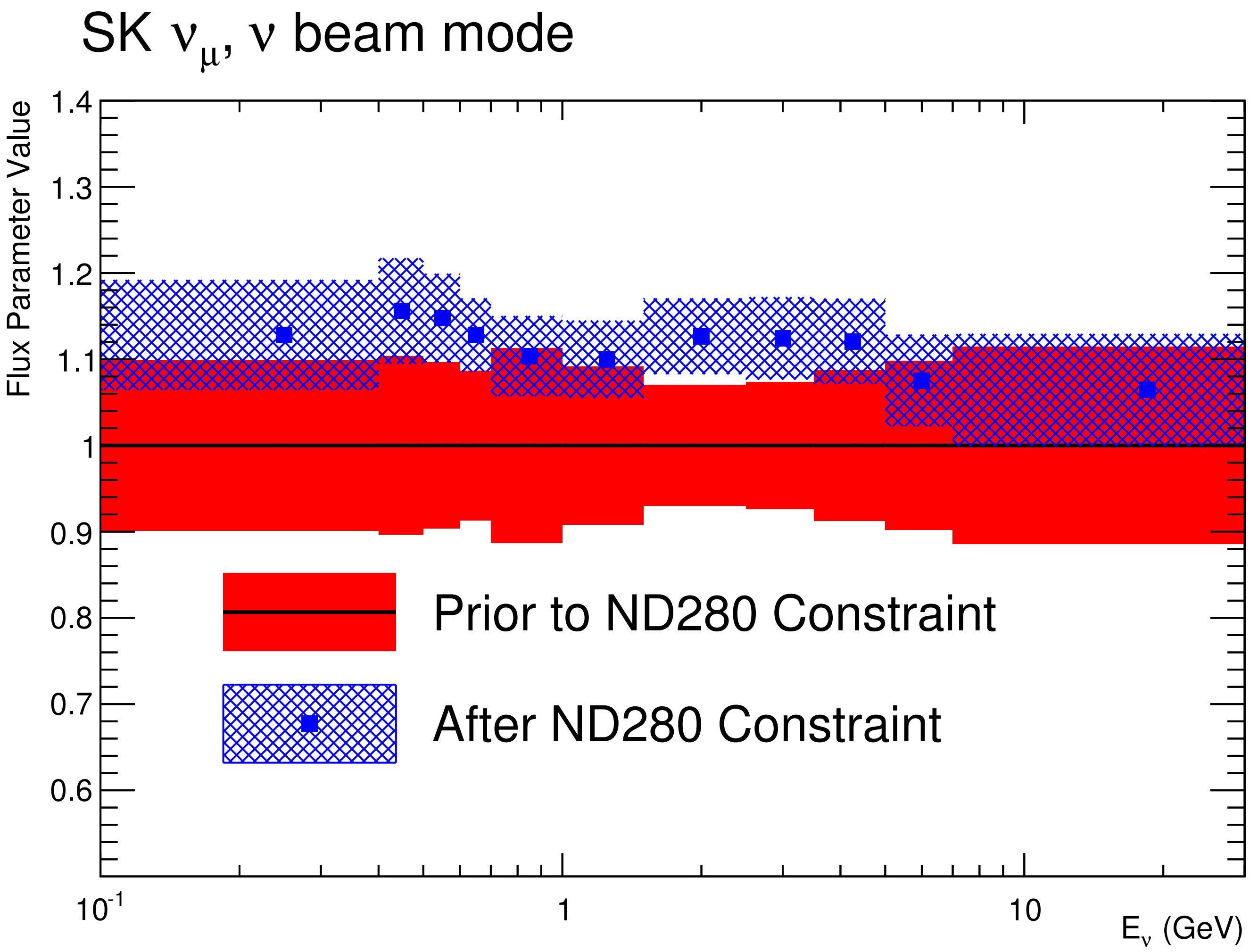
- Prefit spectra are underestimated for CC0π and CC other, but over-estimated for CC1π.

ND280 $\bar{\nu}$-mode pre-fit spectra (FGD1)



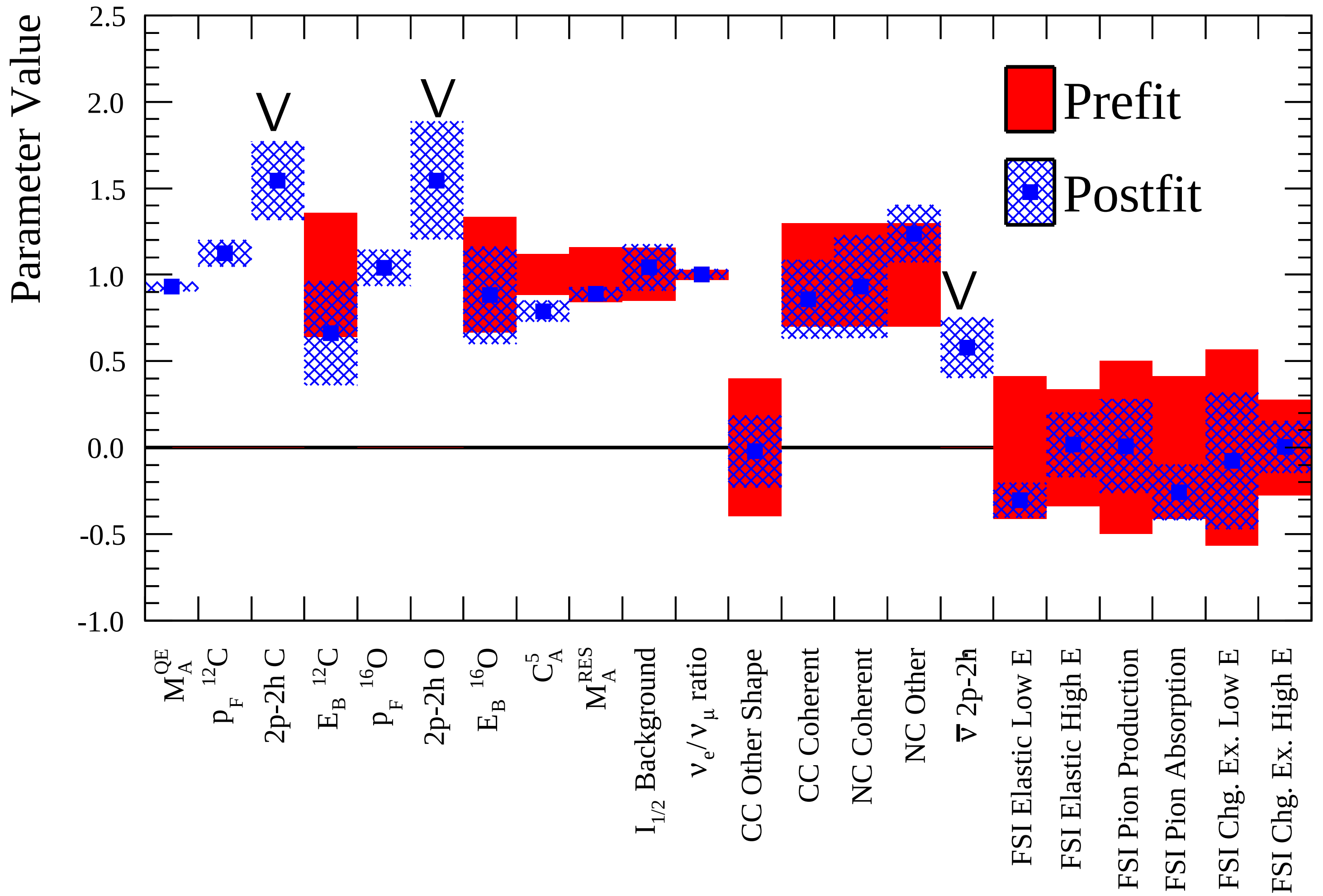
- Lower number of events in $\bar{\nu}$ samples leads to weaker constraints.

ND280 Fit Results (ν_μ flux at SK)



Note - flux parameters generally increased by approximately 10%.

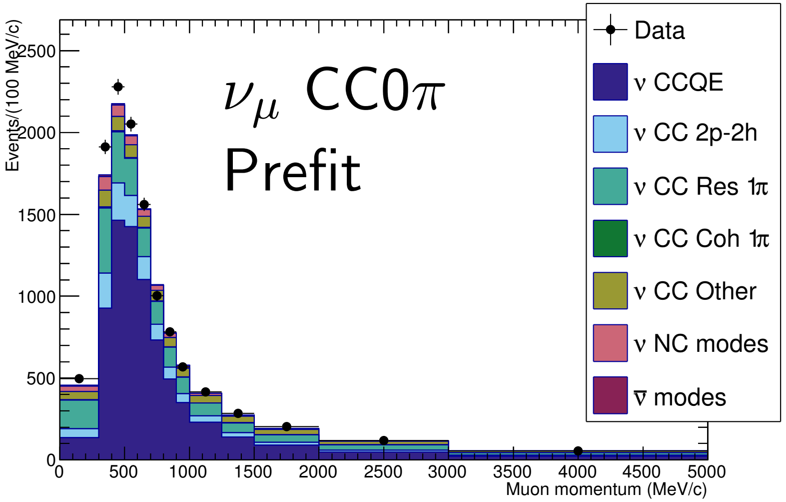
ND280 Fit Results (interaction systematic uncertainties)

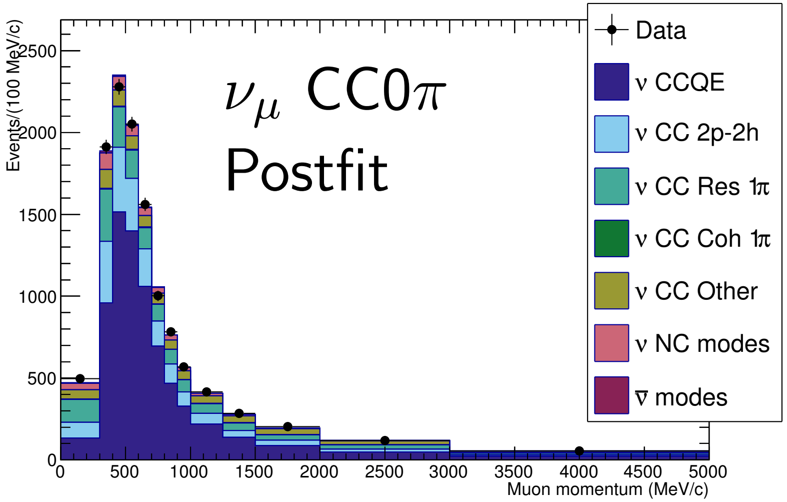


2p2h parameters have moved far from their initial values (at 1).

Note parameters here are ratio-to-nominal, so M_A^{QE} plotted at 0.93 represents a value $0.93 \times 1.21 = 1.12$ GeV.

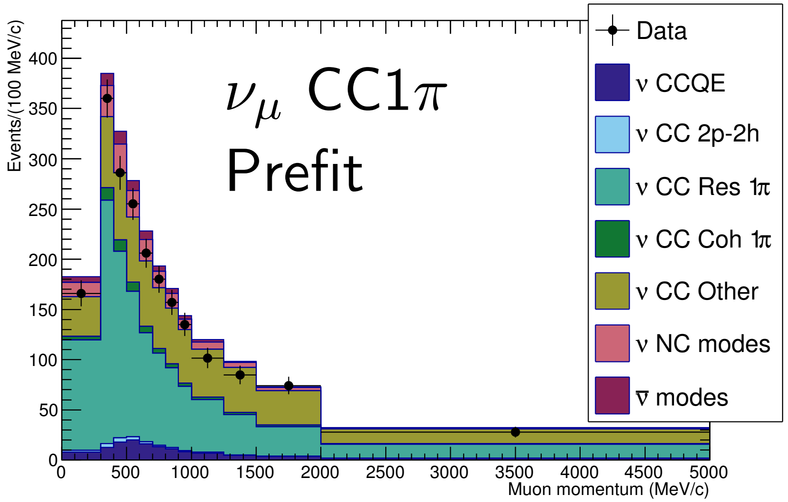
ND280 Postfit Spectrum - CC0π

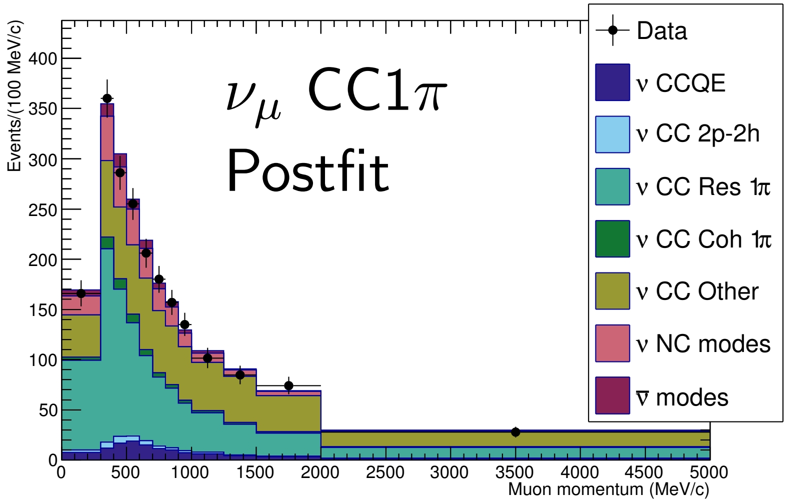




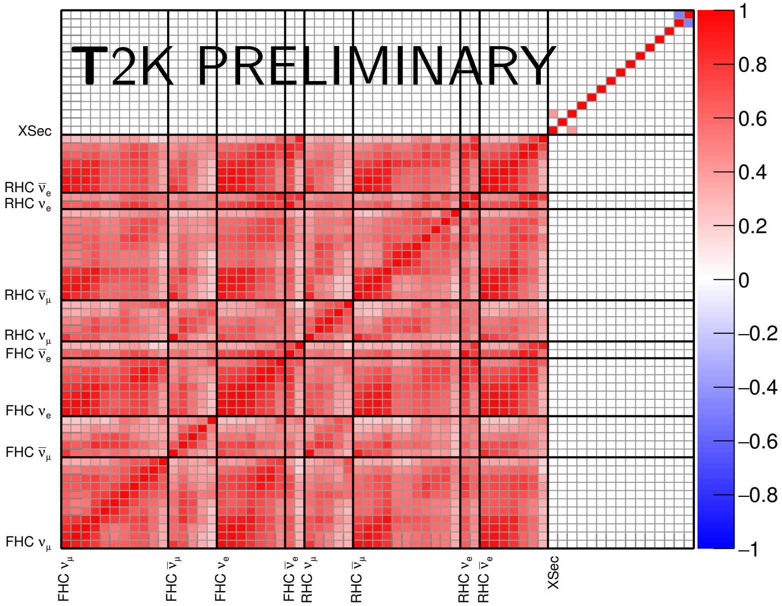
- Agreement with data is clearly improved by fit.
- Noticeable enhancement of 2p2h contribution.

ND280 Postfit Spectrum - CC1π

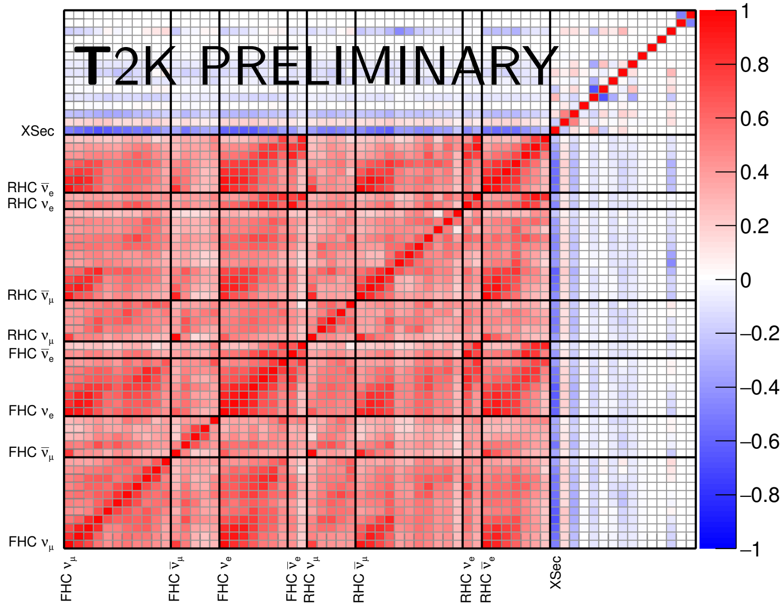




- Total number of events selected as CC1π is reduced.
- Relative fraction of true CC1π resonance events in this sample is also reduced.



Prefit

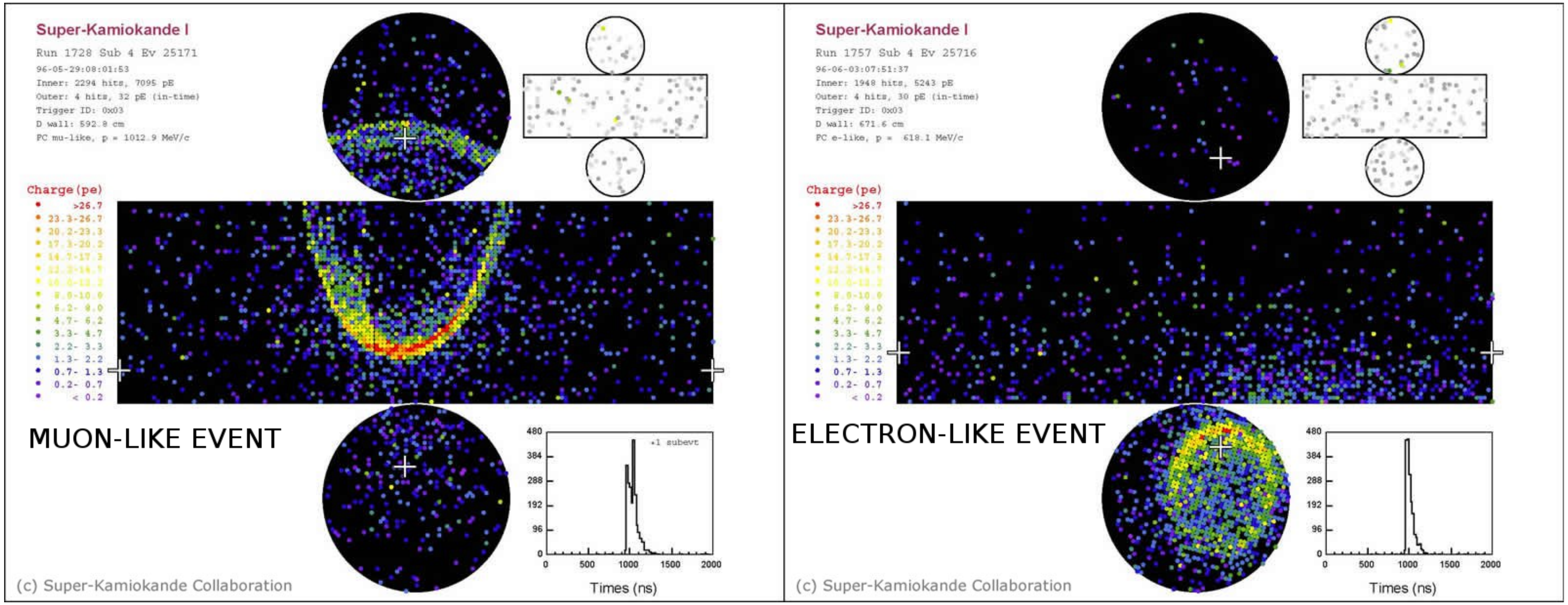


Postfit

As expected, correlations between flux parameters reduced, and we pick up an anticorrelation between flux and interaction parameters (particularly M_A^{QE}, the first interaction parameter).

Super-K Analysis Reminder

Primary event samples - single ring muon-like or electron-like events.



The single ring (CC0π) samples aim for QE-like or 2p2h-like events.
In 2017 analysis, now additionally including ν_e CC1π events!

Uncertainties on Super-K Event Rates

Source of uncertainty	$\delta N_{SK}/N_{SK}$ Asimov A
SKDet+FSI+SI	3.47%
FSI+SI	2.50%
SKDet	2.45%
Flux	3.66%
MEC (corr)	3.90%
MECbar (corr)	0.05%
NC 1gamma (uncorr)	1.46%
XSec nue/numu	2.63%
XSec Tot	5.14%
Flux+XSec	4.12%
Flux+XSec (Pre ND280)	11.47%
Oscillations	0.49%
All	5.53%
All (Pre ND280)	12.06%

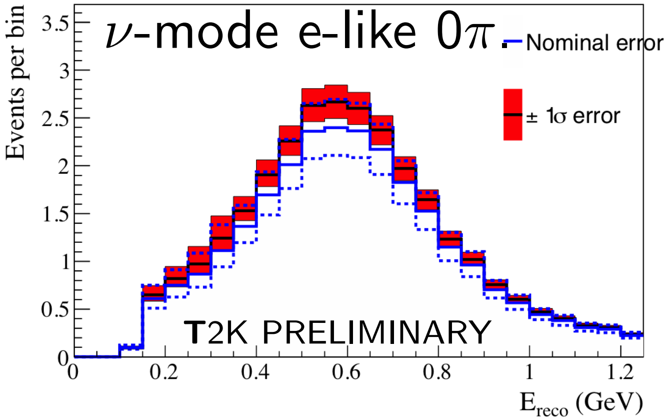
ν-mode e-like.

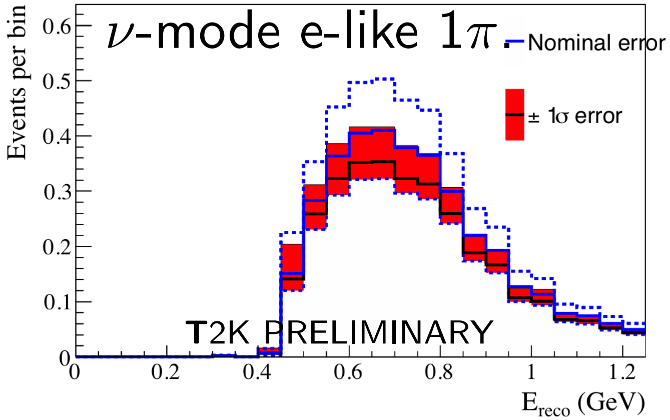
Source of uncertainty	$\delta N_{SK}/N_{SK}$ Asimov A
SKDet+FSI+SI	3.85%
FSI+SI	2.45%
SKDet	3.00%
Flux	3.83%
MEC (corr)	3.03%
MECbar (corr)	2.35%
NC 1gamma (uncorr)	2.98%
XSec nue/numu	1.49%
XSec Tot	5.50%
Flux+XSec (Pre ND280)	4.67%
Flux+XSec	13.38%
Oscillations	0.27%
All	6.31%
All (Pre ND280)	14.06%

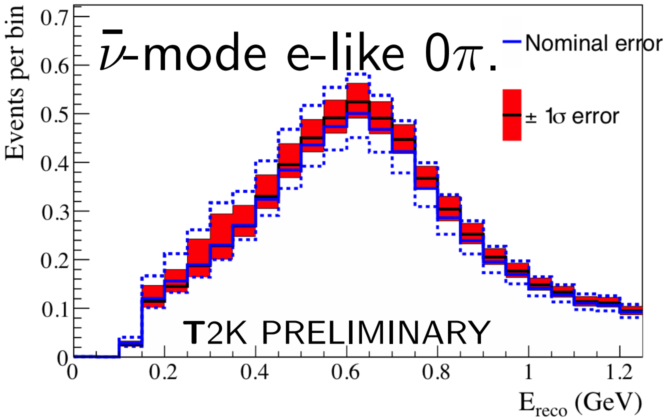
$\bar{\nu}$-mode e-like.

- ND280 effectively reduces the uncertainties on the combination of flux and interaction systematics.
- 2p2h (MEC) is still a large effect.

Uncertainties on Super-K spectra due to all systematic uncertainties







Blue (nominal) is before ND280 fit. Red is after ND280 fit.

As propagated from ND280, decrease in 1π events and an increase in 0π events compared to nominal MC.

Fake-Data Studies

- To evaluate the effects of different models on the T2K results:
  - Select alternative set of MC models.
  - Generate fake dataset for this true model, without statistical fluctuations.
  - Fit using the MC and uncertainties used in the official fits.
  - If necessary, update our parameterisation to be appropriate.
  - Compare to baseline model equivalent (Asimov).
- Fake-data fits were performed with the accumulated POT up to Run 6 (1.1×10^{21}).
- We use these results to suggest additional uncertainty parameters that must be included.

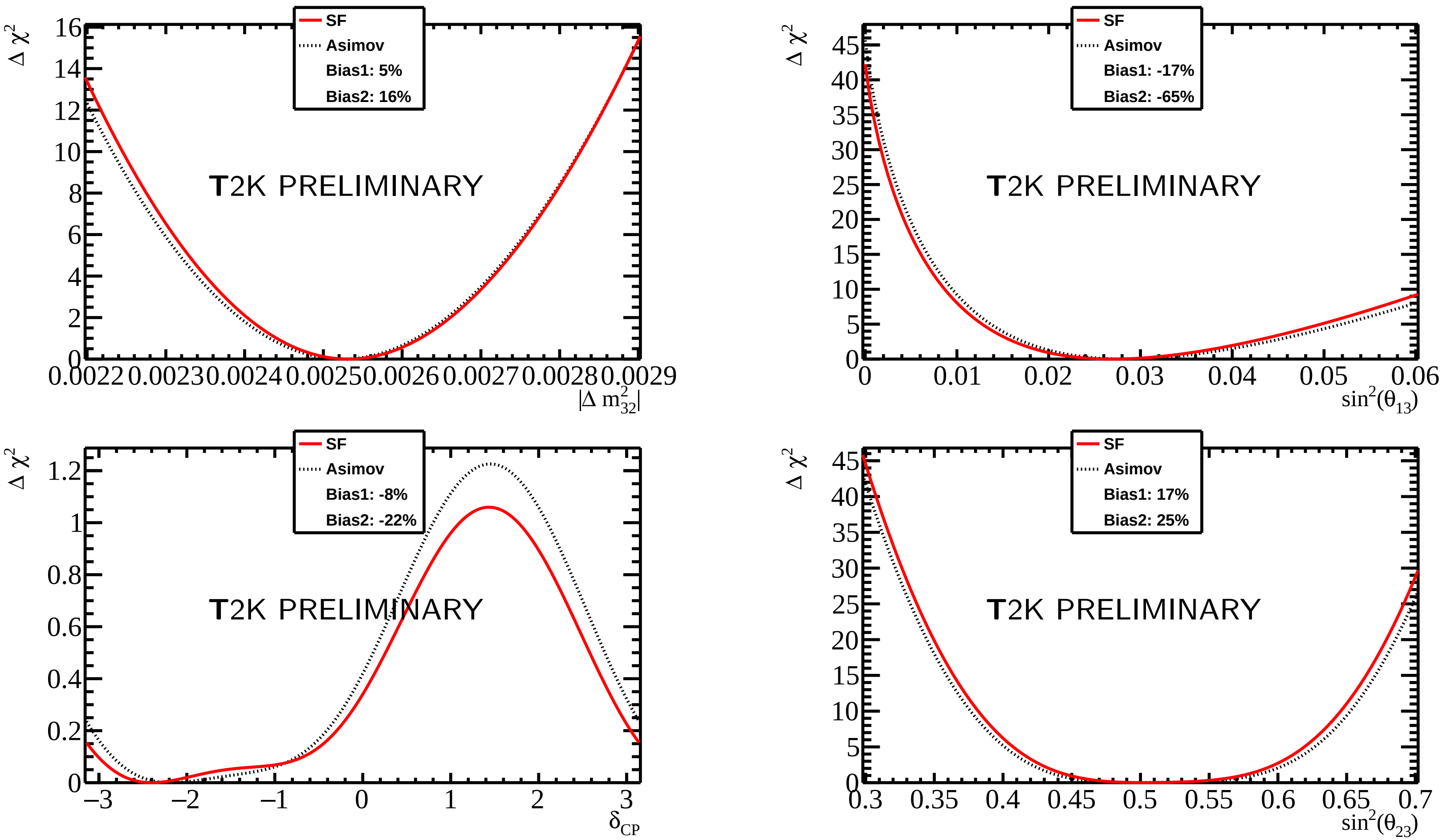
Baseline NEUT Model Used

- NEUT v5.3.3
- Llewellyn-Smith CCQE calculation with $M_A^{QE} = 1.21\ \mathrm{GeV}$.
- By default, this version of NEUT uses the Spectral Function (O. Benhar) nuclear model.
- Motivated by external data fits, T2K instead uses the global Relativistic Fermi Gas nuclear model (Smith-Moniz, 1971), with an additional correction for the relativistic Random Phase Approximation (RPA) by Nieves.
- 2p2h provided by the Nieves model.

Additional Models used for fake data as implemented in NEUT

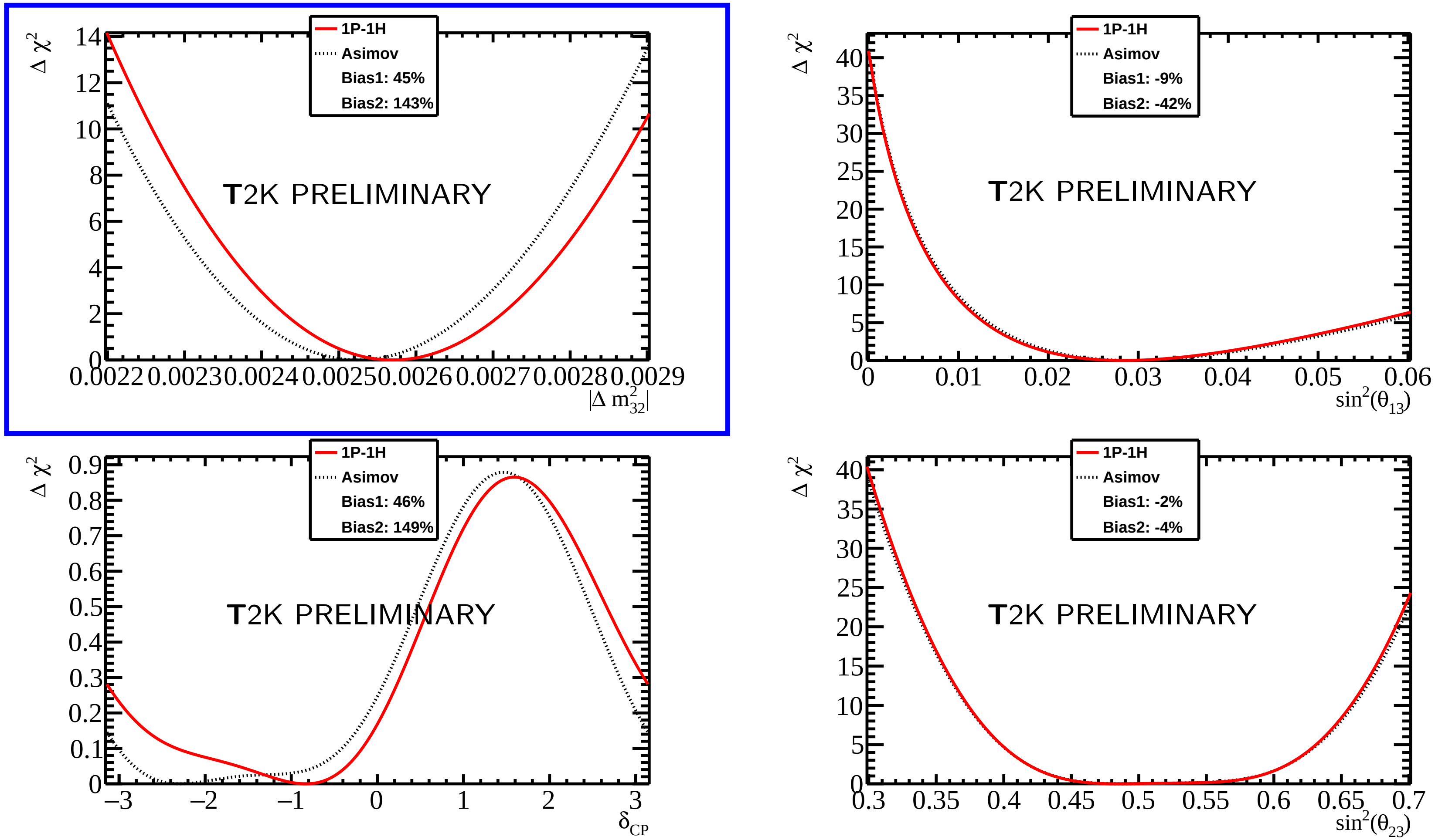
- Spectral Function (O. Benhar et al. PRD 72, 053005, 2005).
  - Model of O. Benhar with no RPA. $M_A^{QE} = 1.33\ \mathrm{GeV}$ and no 2p2h, motivated by external data fits.
- Nieves 1p1h (J. Nieves et al. PRC 83, 045501, 2011)
  - Uses Local Fermi Gas nuclear model, includes long range nucleon-nucleon correlations for RPA.
  - Significant change to muon $p - \theta$ distribution.
- Martini 2p2h (Martini et al. PRC 84, 055502, 2011)
  - Martini 1p1h similar to Nieves 1p1h.
  - Most significant difference - more ν 2p2h around T2K flux peak of 0.6 GeV, but not more $\bar{\nu}$.
- Effective RPA
  - Flexible RPA model with 5 free parameters, fitted to MiniBooNE and MINERνA data.

Spectral Function Fake-Data Fits ($\delta_{CP} = -1.601$)



Bias small at current POT. Will become significant at full T2K POT.
No new uncertainty needed yet.

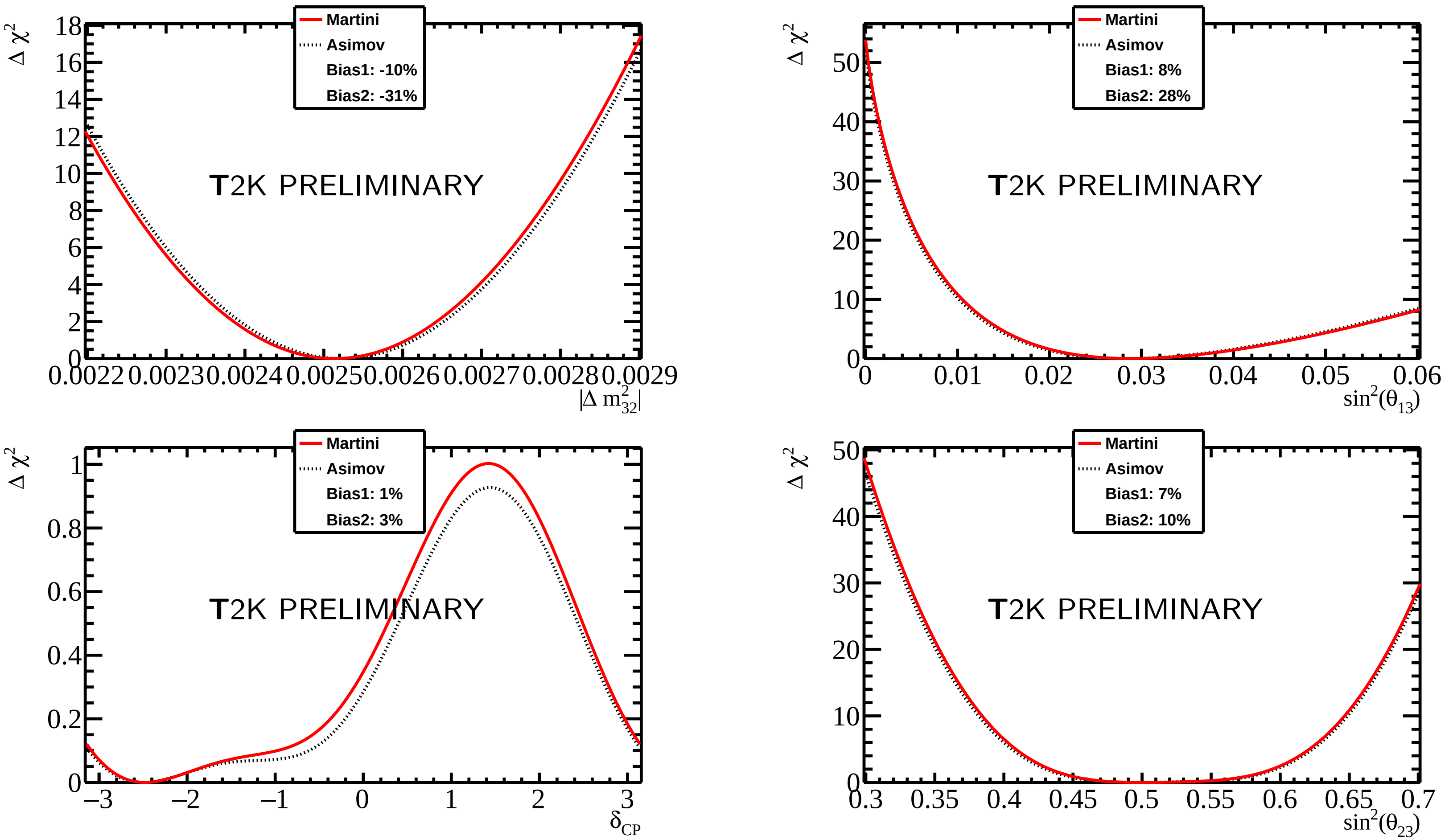
Nieves 1p1h Fake-Data Fits ($\delta_{CP} = -1.601$)



Significant bias in Δm^2_{32} due to difference in reconstructed neutrino energy distribution.

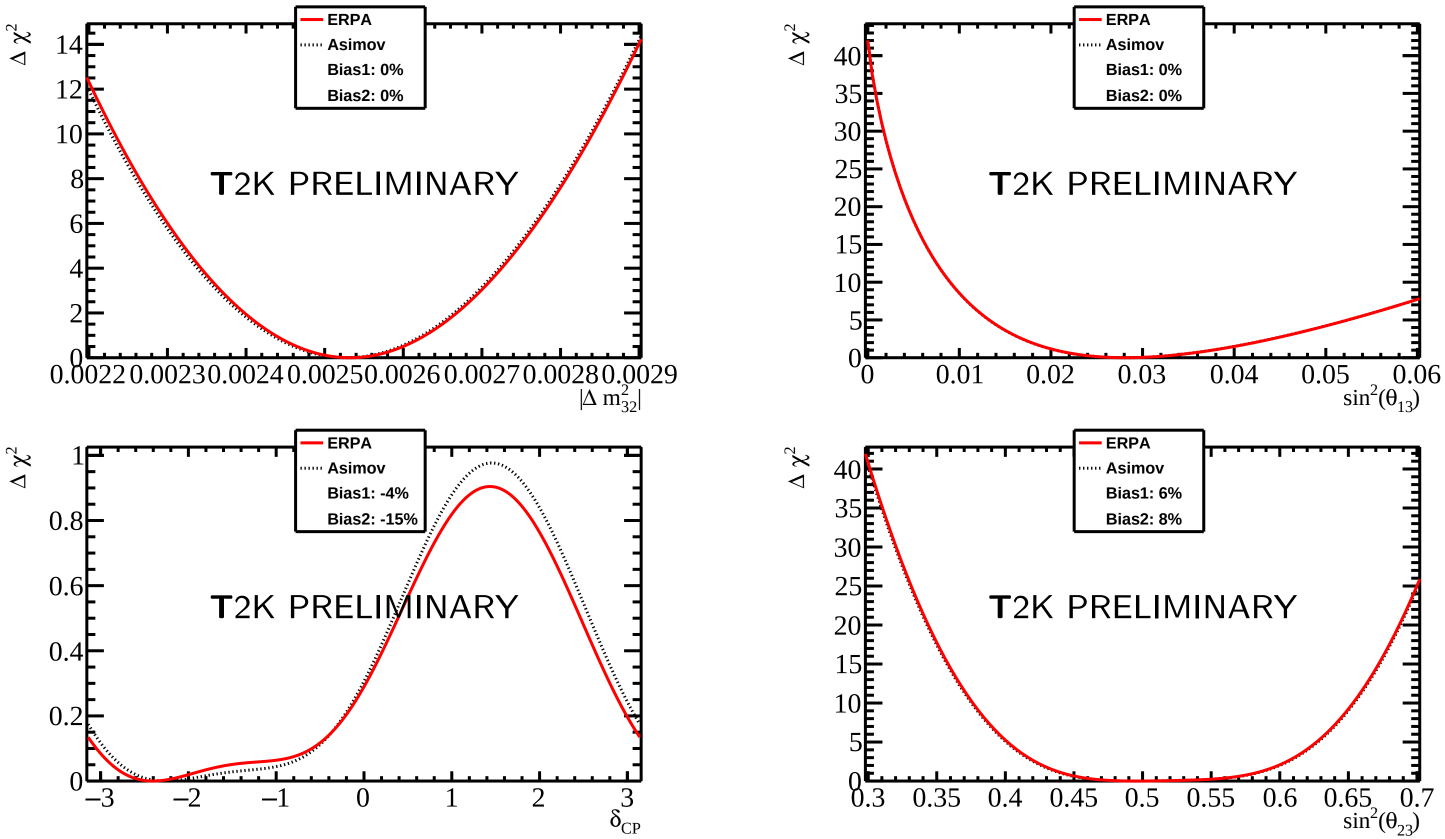
- This motivated the addition of an extra detector uncertainty for this year's results.

Martini 2p2h Fake-Data Fits ($\delta_{CP} = -1.601$)



The addition of the $\bar{\nu}$ MEC uncertainty parameter makes this model fit appropriately at current POTs.

Effective RPA Fake-Data Fits ($\delta_{CP} = -1.601$)



Effect of this model change is negligible.

Fake-Data fits Summary

- Spectral Function has a small effect at our current POT.
- The different energy distribution from the Nieves 1p1h model adds a significant bias in Δm^2_{32}, and motivates an extra detector uncertainty.
- The differences between the Martini and Nieves 2p2h models are mostly handled by the addition of the $\bar{\nu}$ 2p2h uncertainty.
- The effective RPA model has a negligible effect on the oscillation fits.
- **Some of the effects which are small now will become significantly larger at T2K full exposures**.
  - Model dependent effects are going to get important before we finish the initial T2K running goal.
- All of these fake data studies will be included in detail in our upcoming long oscillation paper.
  - Look out for it!

Conclusions

- T2K has a powerful near detector that allows us to constrain our flux and interaction systematic uncertainties for oscillation fits.
  - Flux and interaction systematics result in a 5% event rate uncertainty on our ν_e and $\overline{\nu_e}$ samples at Super-K.
  - Inclusion of Super-K detector uncertainties leads to a 6% total event rate uncertainty.
- Our default event rate prediction is low for CC0π events and high for CC1π events.
  - The ND280 data fit leads us to increase neutrino flux but decrease CC1π cross-sections.
  - and also increase our predicted 2p2h contribution by around 50% for neutrinos.
- Fake-data has informed our parameterisation, and shown that it is sufficient for the current T2K exposures.
  - But fake-data fits at our full exposure suggest that these effects will become more important.
  - So the ongoing work of the community to help improve our models and their uncertainties is greatly appreciated!

Section 1

Backup