T2K Near Detector Fit

Near detector constraint on the T2K 2020 neutrino oscillation analysis

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On behalf of the T2K Collaboration

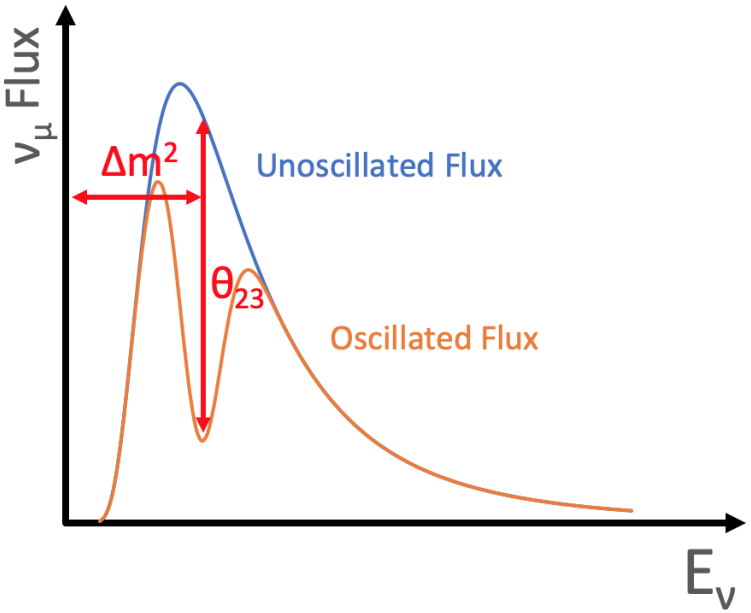
Measuring Oscillation Parameters

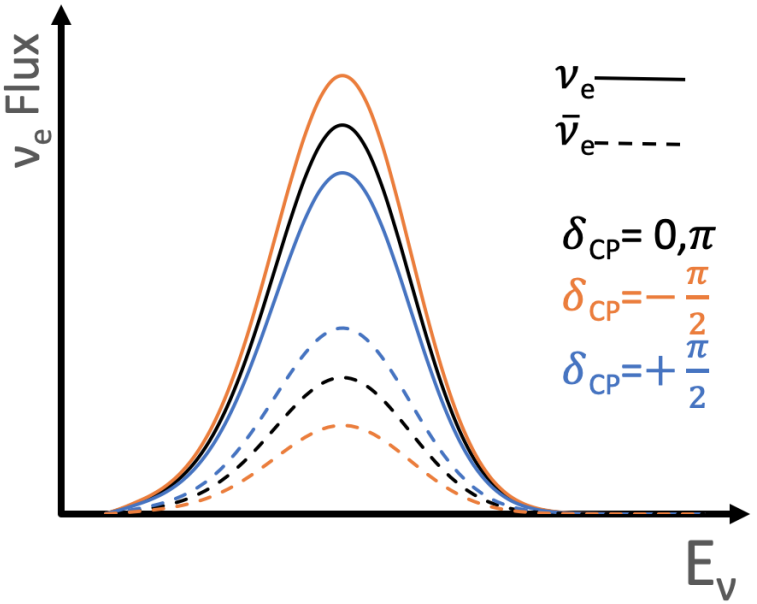
Assuming 3 flavour PMNS mixing in a pure ν_μ beam with fixed baseline L the only remaining free parameter is the neutrino energy E_ν.
The strength of CP violation is encapsulated by the J_{CP} term

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \sin^2\left(1.27\Delta m^2_{32} \frac{L}{E_\nu}\right)$$

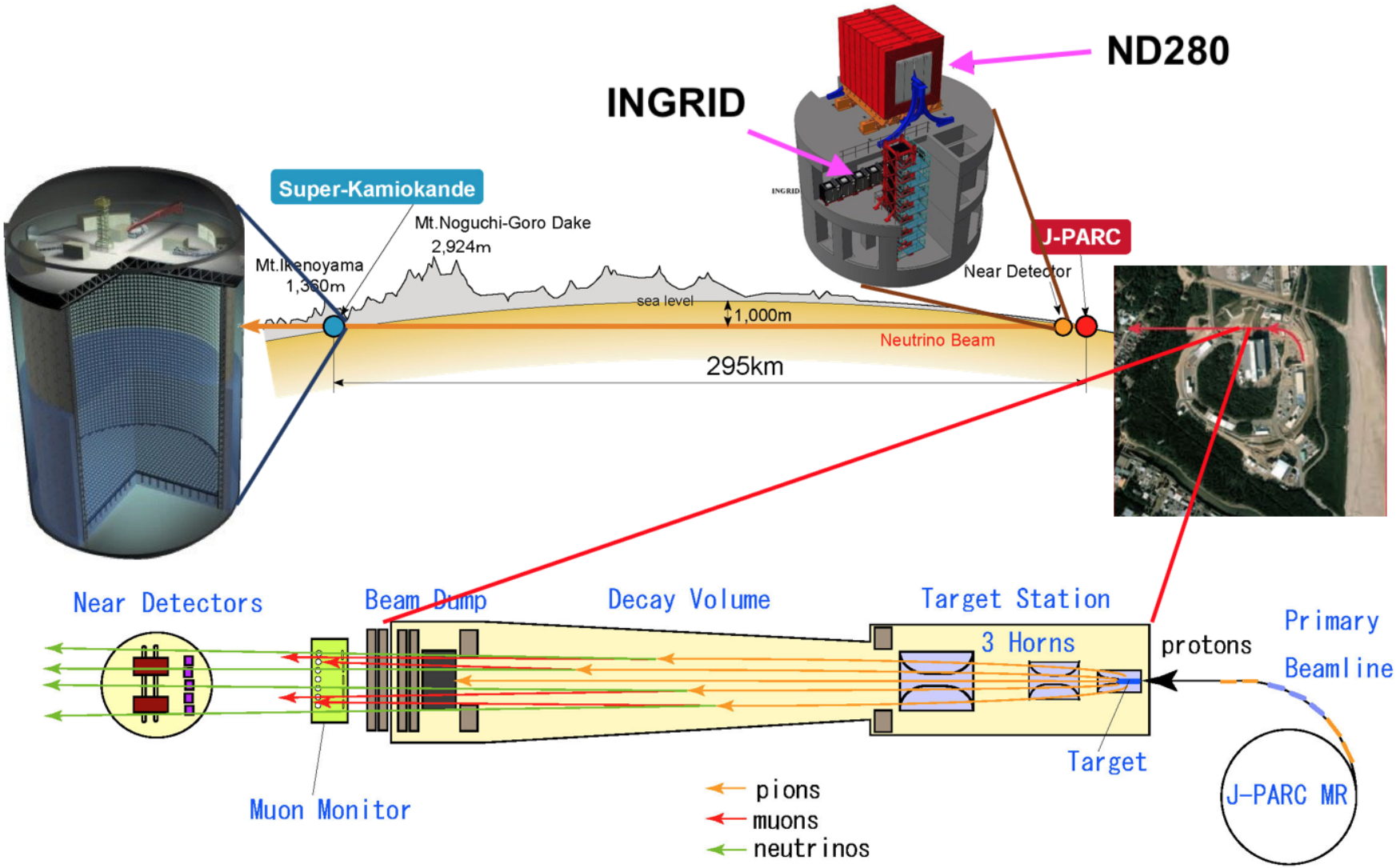
$$P(\nu_\mu \to \nu_e) \simeq \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2\left(1.27\Delta m^2_{32} \frac{L}{E_\nu}\right)$$

$$\mp 1.27\Delta m^2_{32} \frac{L}{E_\nu} 8 J_{CP} \sin^2\left(1.27\Delta m^2_{32} \frac{L}{E_\nu}\right)$$





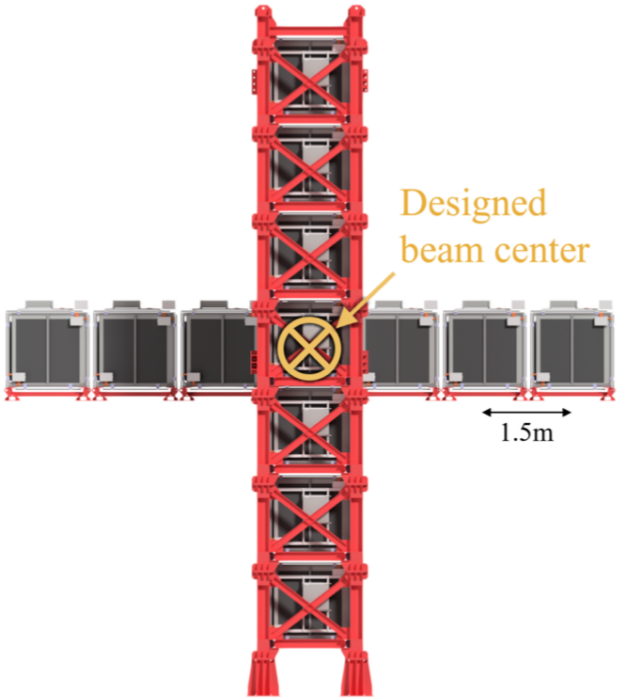
The T2K Experiment

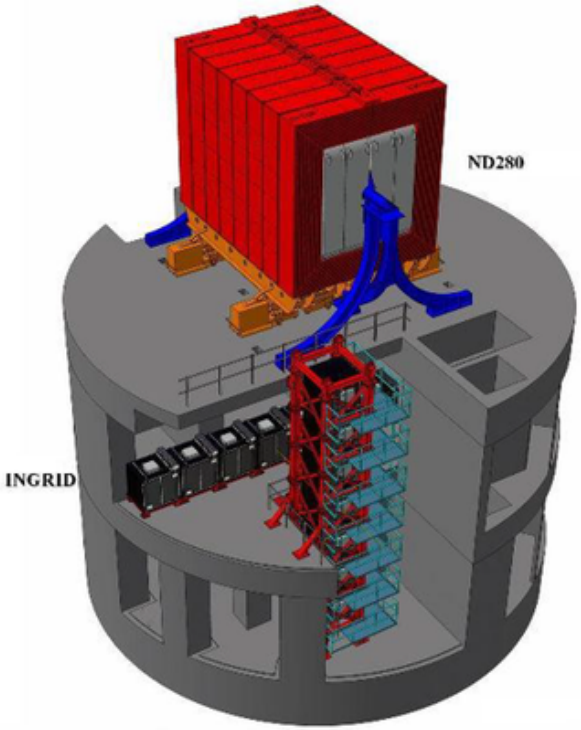


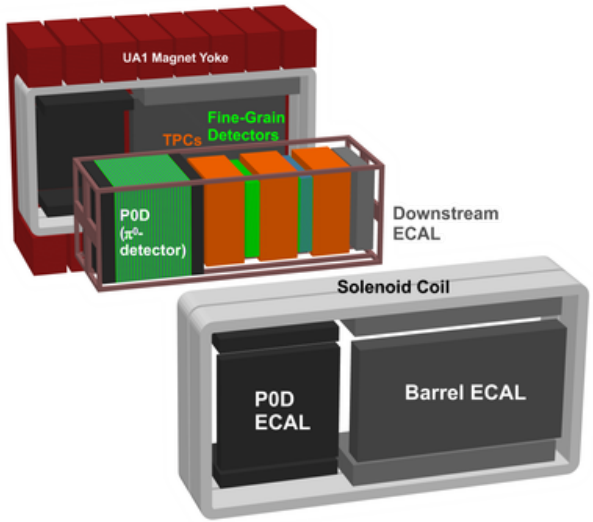
Changing magnetic horn polarity can select for neutrinos or antineutrinos

ND280 Suite

Two near detectors in this analysis.
280 m downstream from the target.







INGRID

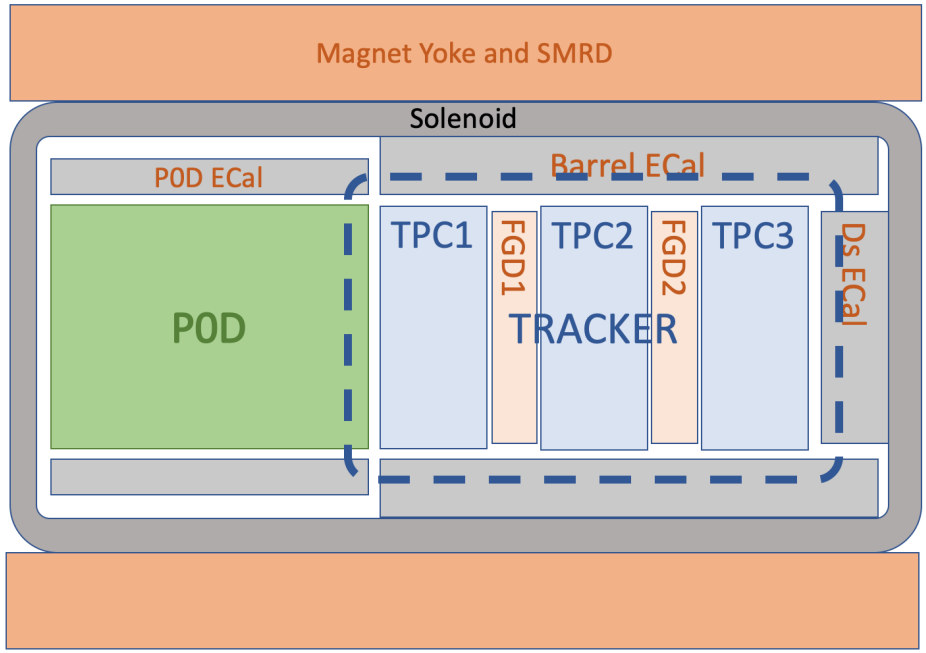
ND280

On-axis
Iron-plastic scintillator
Measures direction
and intensity

Off-axis
Plastic Scintillator
and Water targets for
detailed interaction studies

Off-axis magnetised tracking detector used to to study neutrino interactions and constrain cross-section and beam flux models

- Dedicated π^0 detector (P0D)
- Two plastic scintillator Fine Grained Detectors (FGDs)
- Three gaseous argon Time Projection Chambers (TPCs)
- Lead scintillator electromagnetic calorimeter (ECals)
- Solenoid magnet and yoke
- Side Muon Range Detector (SMRD) instrumented in magnet



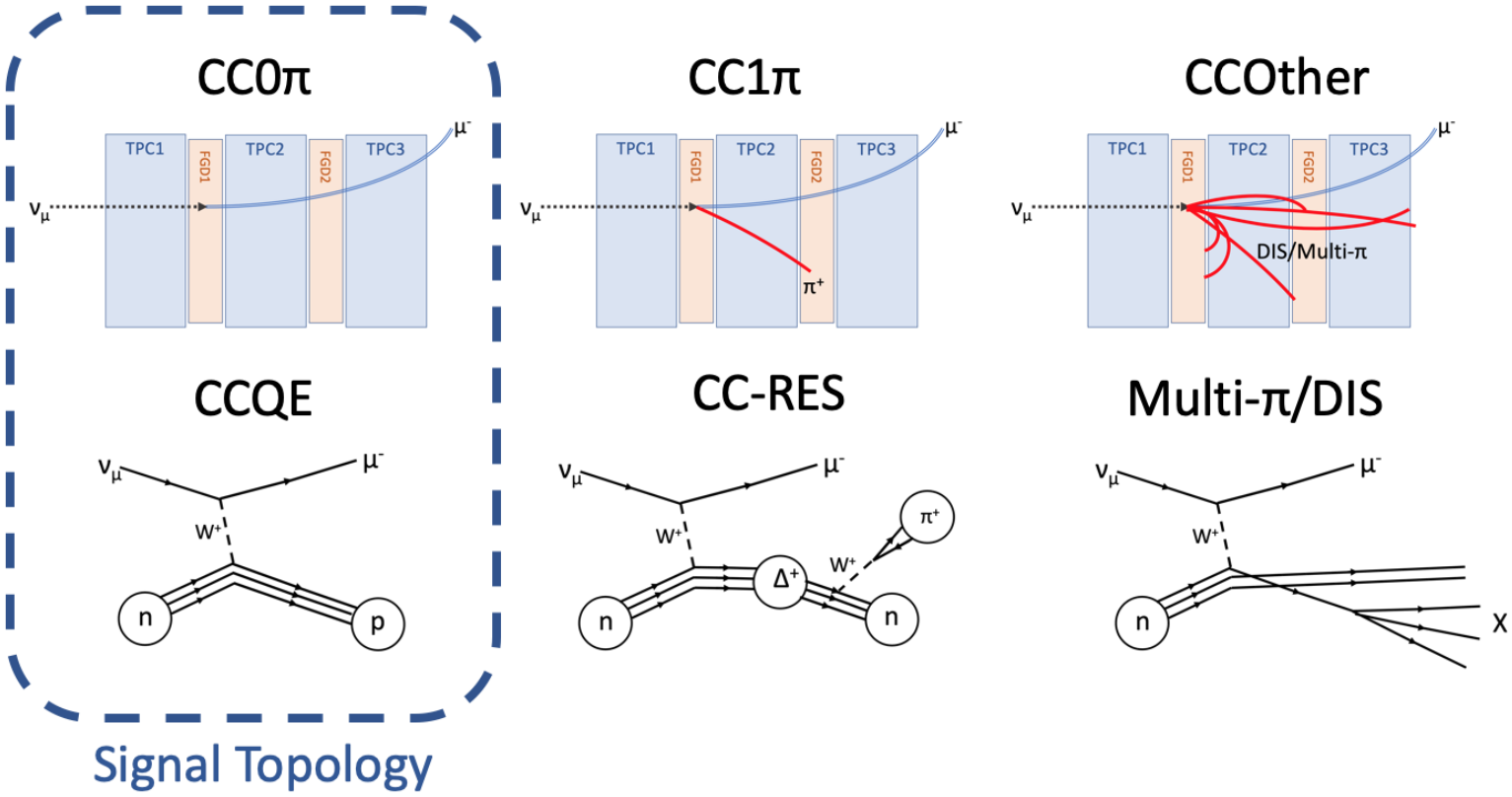
Tracker region is used for T2K oscillation analysis fits.
FGD2 includes water targets to constrain modelling of interactions on Oxygen which is important for Super-K predictions

ND280 Data Samples

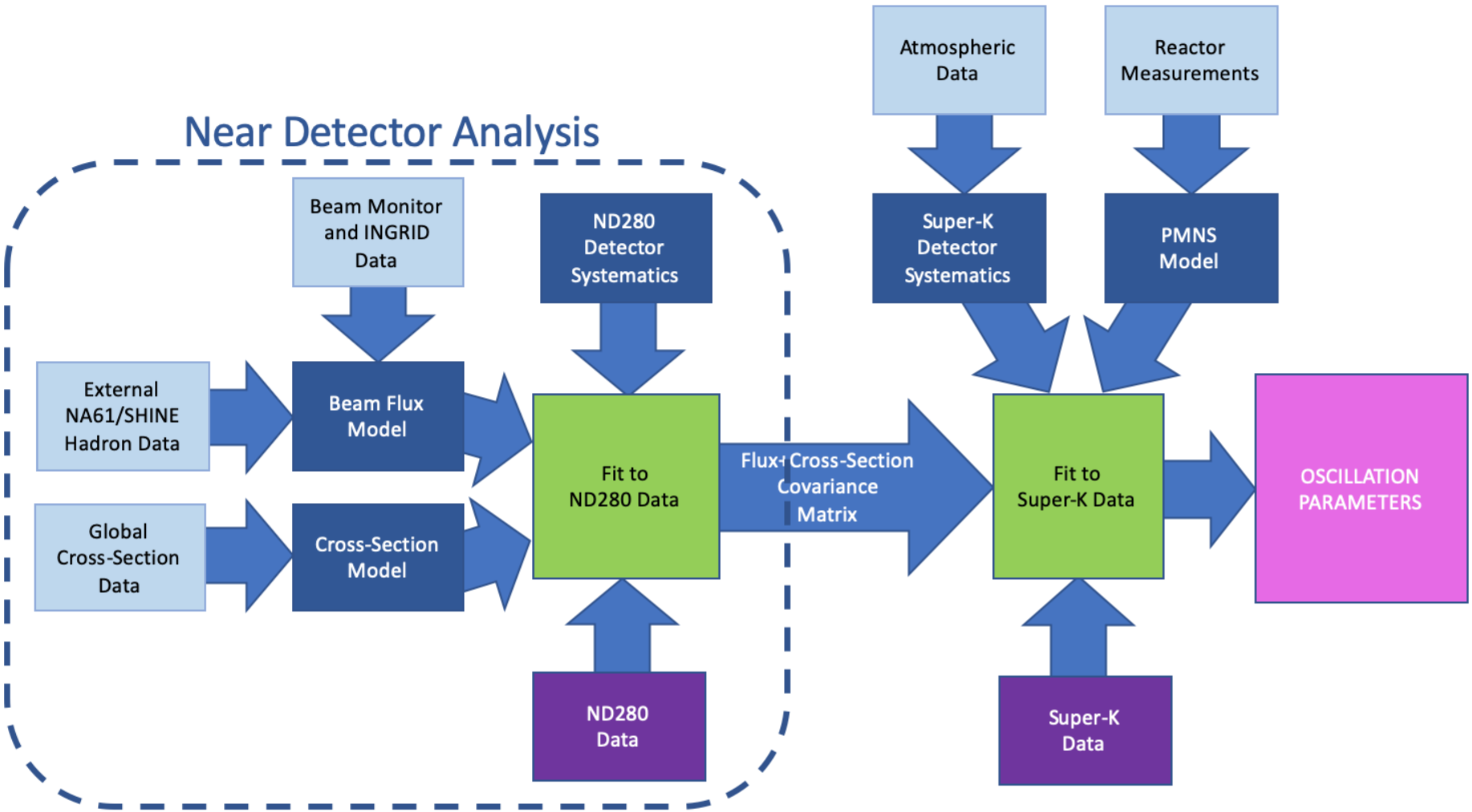
We separate our samples by ν /$\bar{\nu}$ beam mode as well as dedicated ν_μ bkg. in $\bar{\nu}$ beam samples

Target subdetector FGD1/FGD2 (hydrocarbon vs hydrocarbon+water)

Reconstructed pion topology targets specific interaction modes:



Analysis Procedure

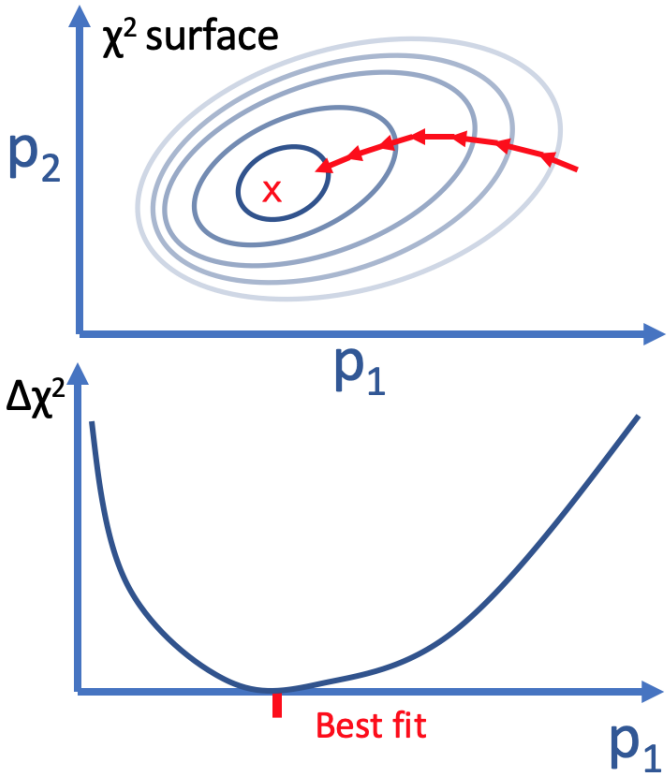


We also do a simultaneous fit producing a posterior probability density function which we cross-validate with at both near and far detector.

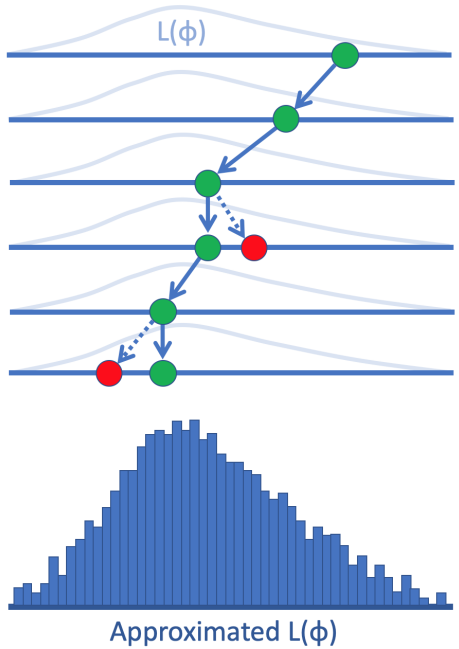
Fitting methods

The two fitting schemes (sequential vs simultaneous) use different methods to find the best fit parameter values and their uncertainties

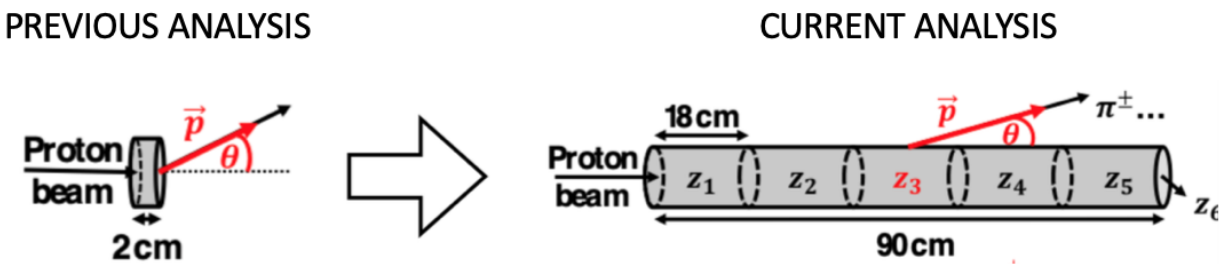
Gradient descent to minimise a $\Delta\chi^2$ surface to find the best fit parameter values.

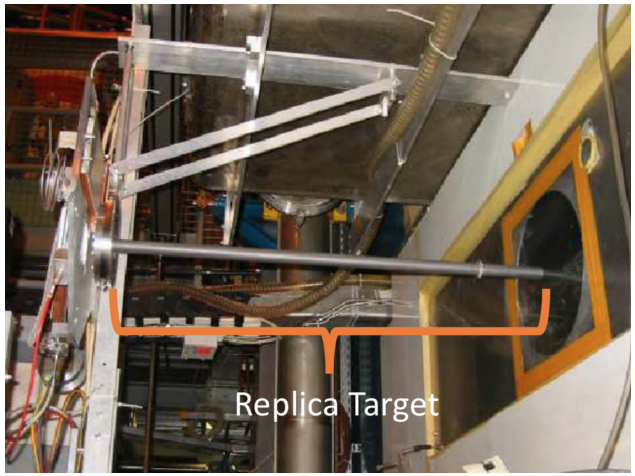


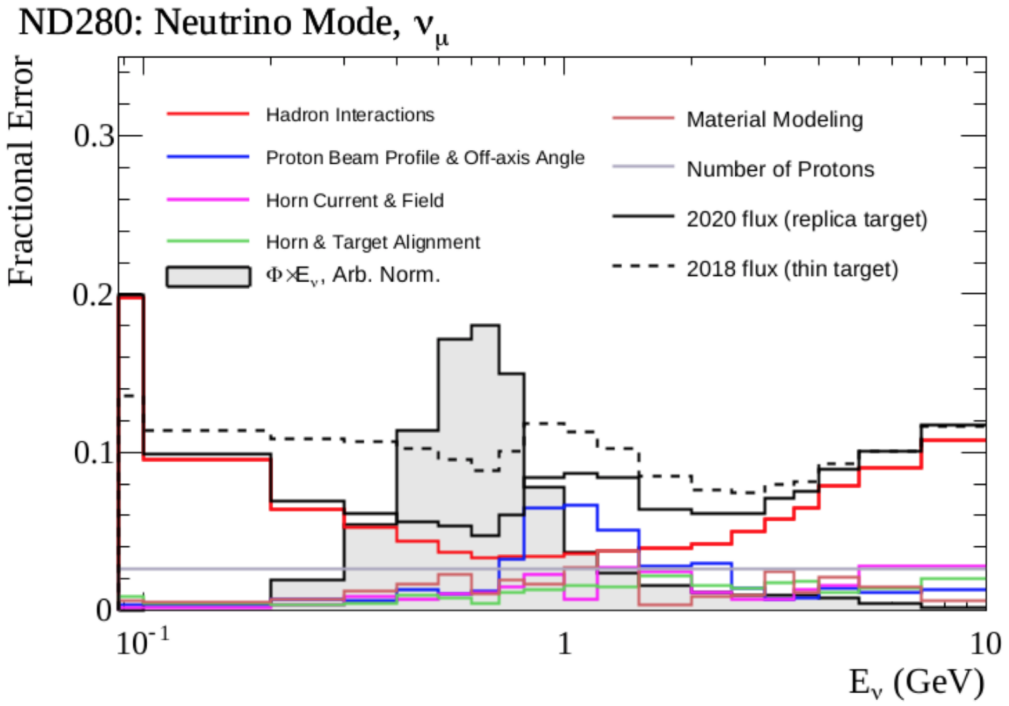
Markov Chain Monte Carlo method stepping through the parameter space and populating a posterior probability density function.



Replica target flux model







In order to constrain beam flux model we use external hadron production data from NA61/SHINE

Previously thin target data
Now T2K replica target data

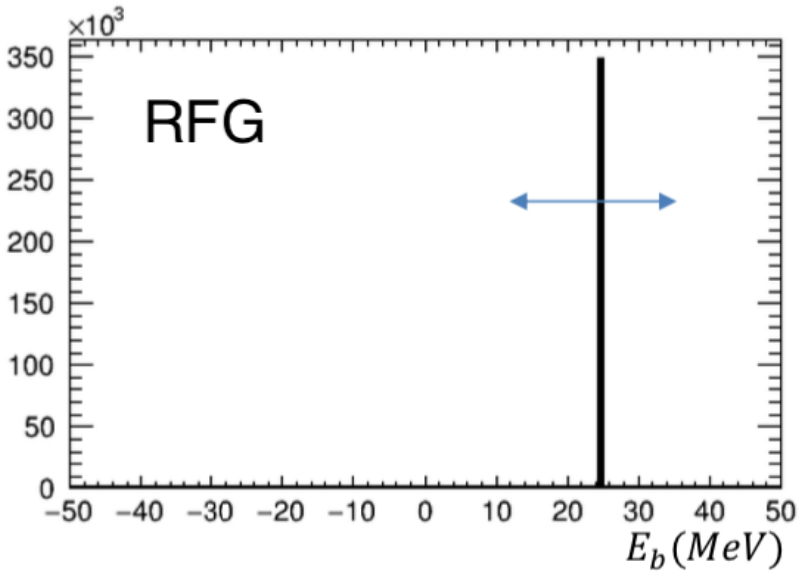
Reduces error in flux peak from 8% to 5%.

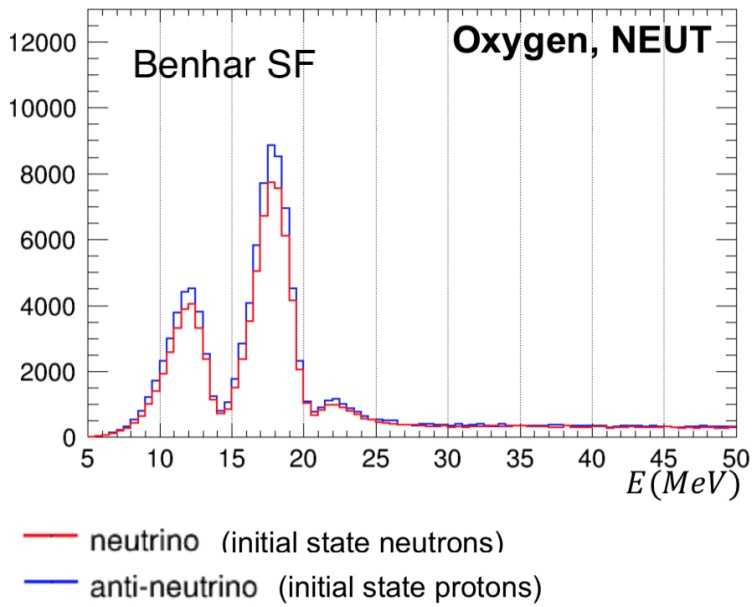
Vladisavljevic T. (2020) https://arxiv.org/abs/1207.2114

Nuclear model update

CCQE nuclear base model no longer Relativistic Fermi Gas model but Benhar Spectral Function informed by external electron scattering data.

More sophisticated treatment of nuclear binding energy in the fit, implemented as a kinematic shift not an event weight.

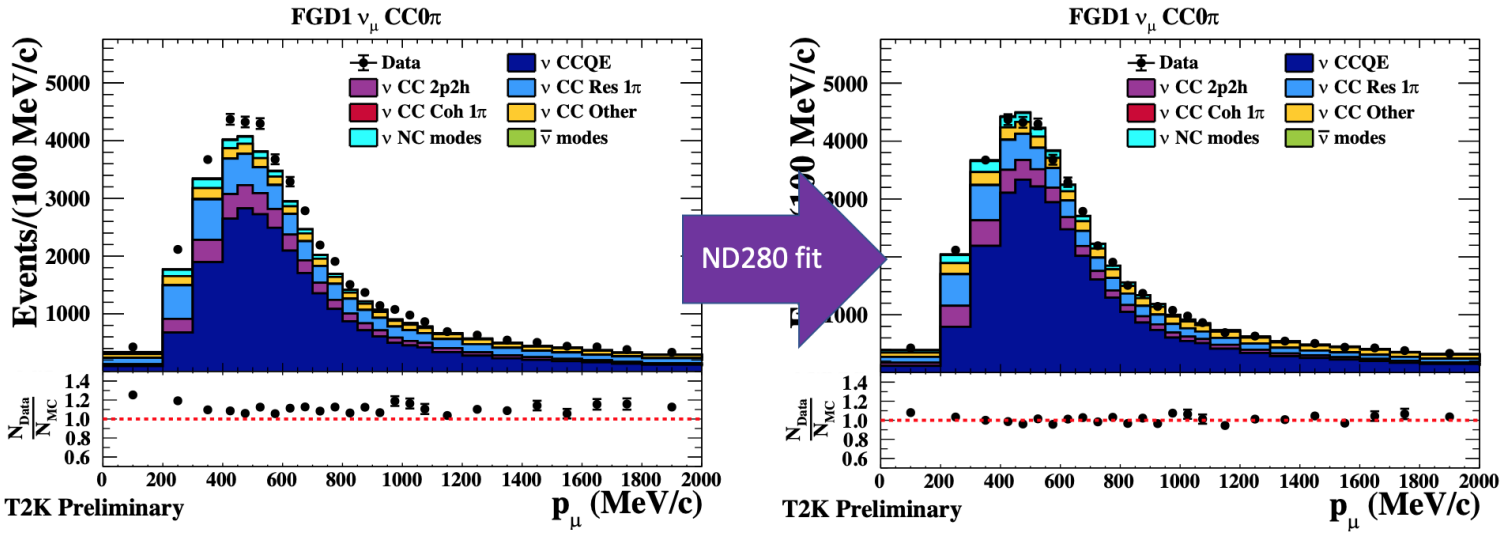




Shift impacts lepton kinematics and E_ν^{rec} which we fit in

Data fit

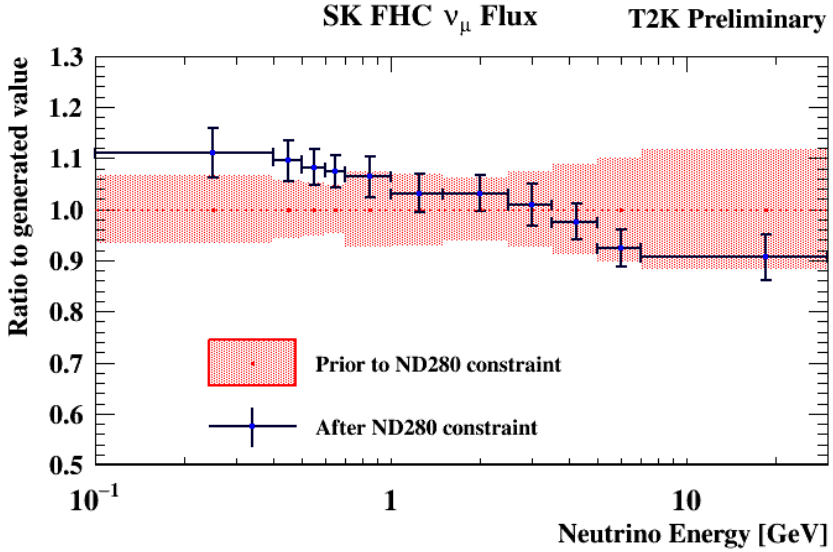
Fit enhances CCQE component of sample. Prefering high Q^2 and low E_ν.



Significant reduction in parameter uncertainties.

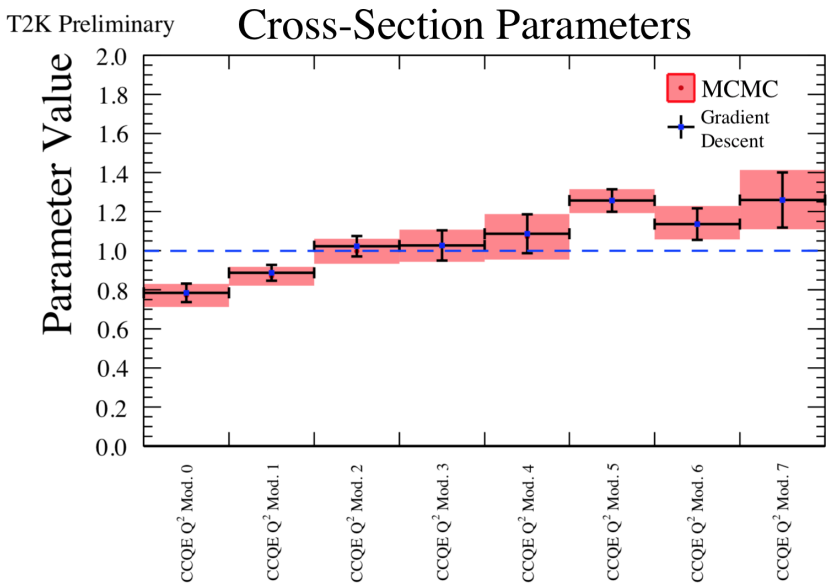
Calculate a p-value of $p = 0.74$
Better than old model $p = 0.5$

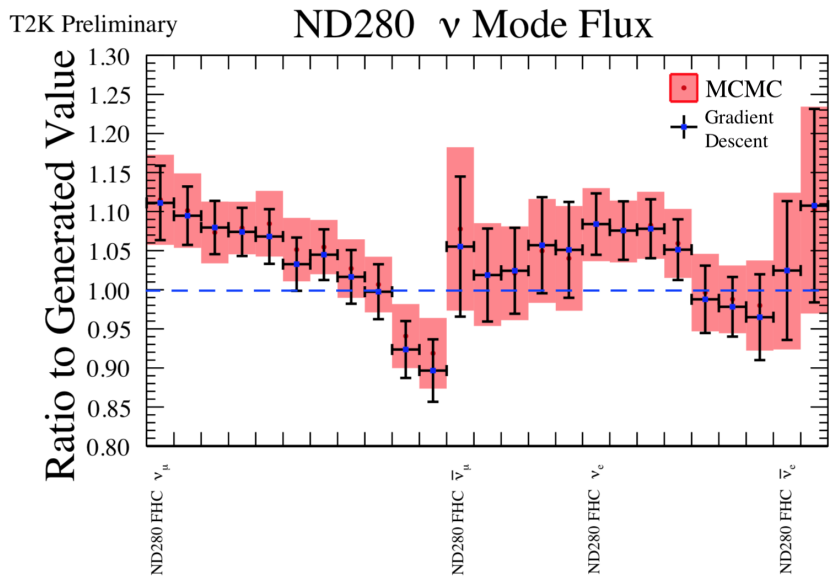
ND280 Data is very consistent with our model



Fitter Comparison at ND280

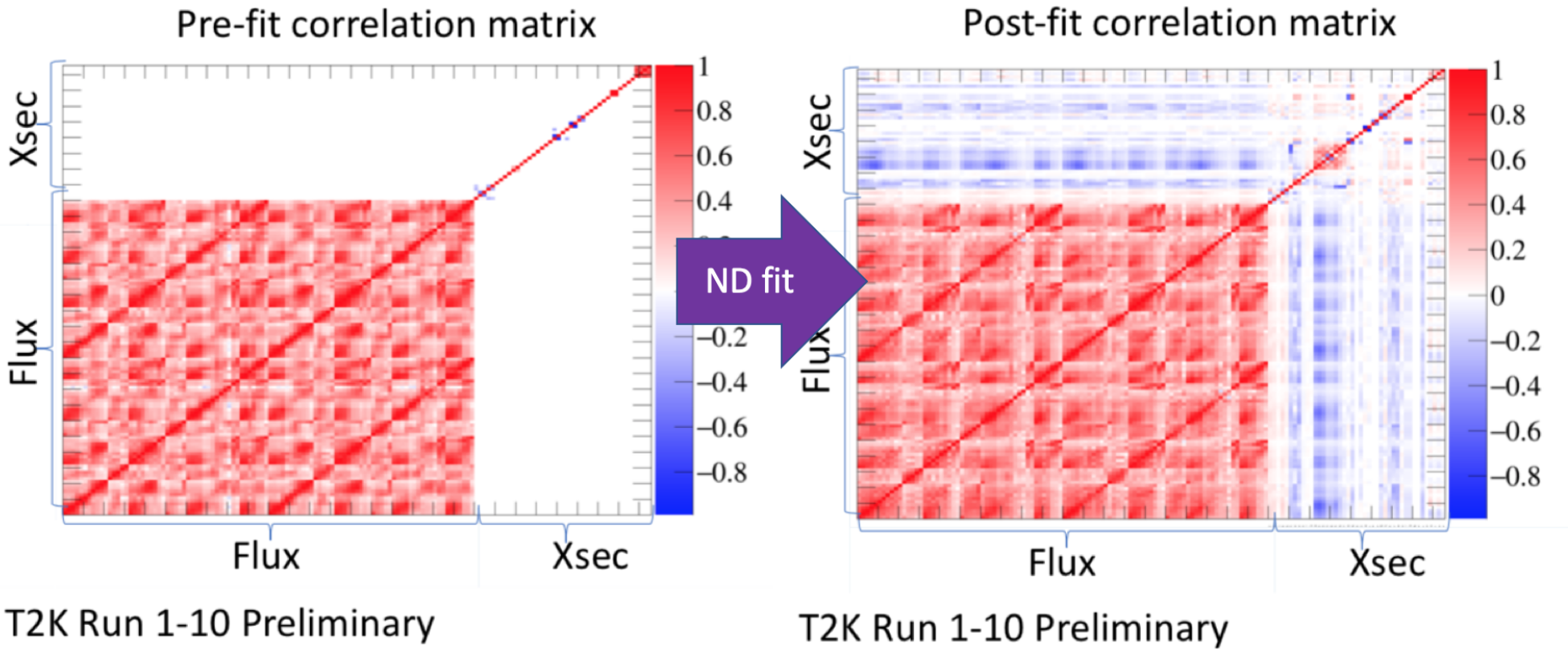
We can do comparisons of sequential and simultaneous fit methods at ND280. Very consistent results despite fundamentally different approaches. (Gradient vs MCMC semi-random walk)





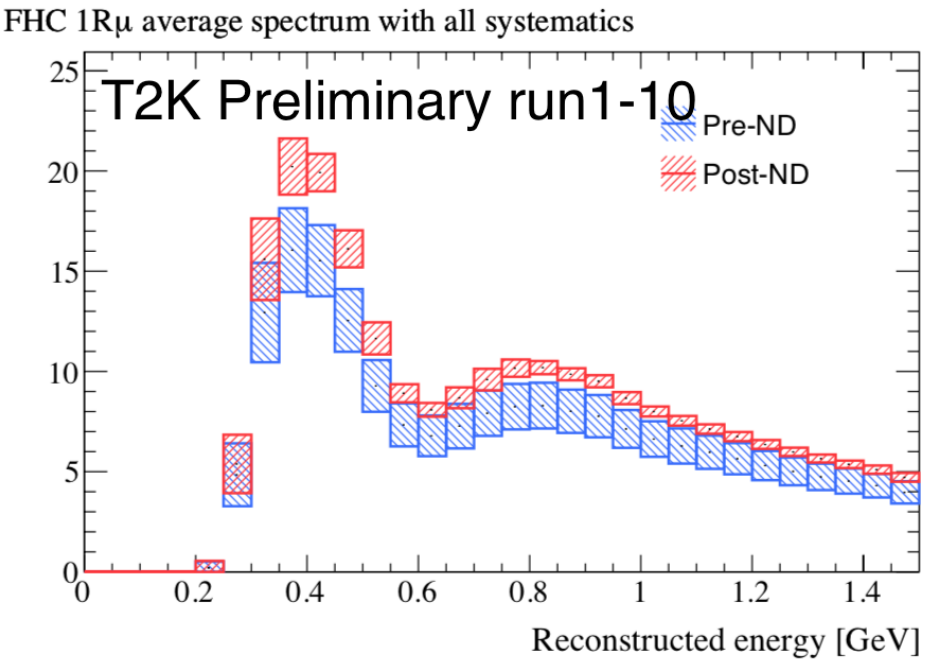
Near Detector Correlations

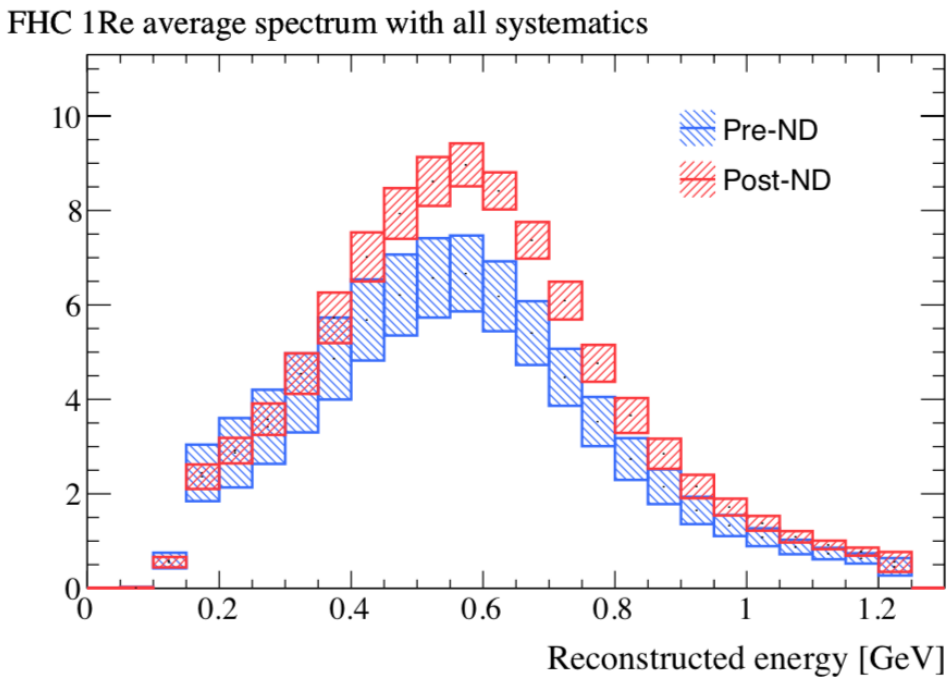
Strong anticorrelations introduced between Flux and XSec parameters.



This is where the power of the ND280 fit factors into our analysis!

ND280 Fit Predictions at Super-K



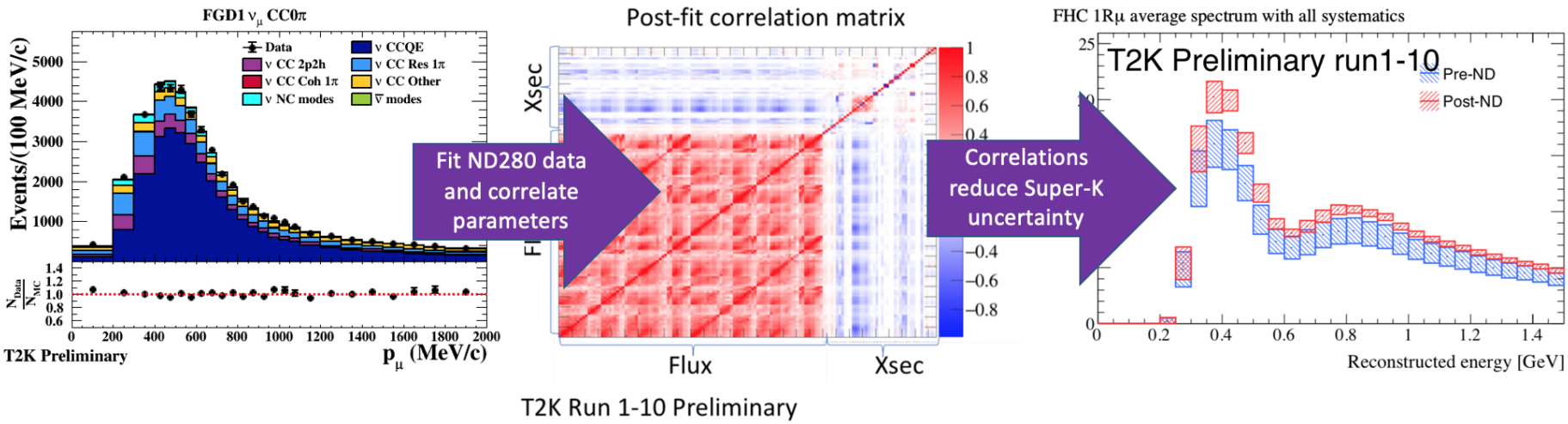


Includes Super-K detector systematic uncertainty

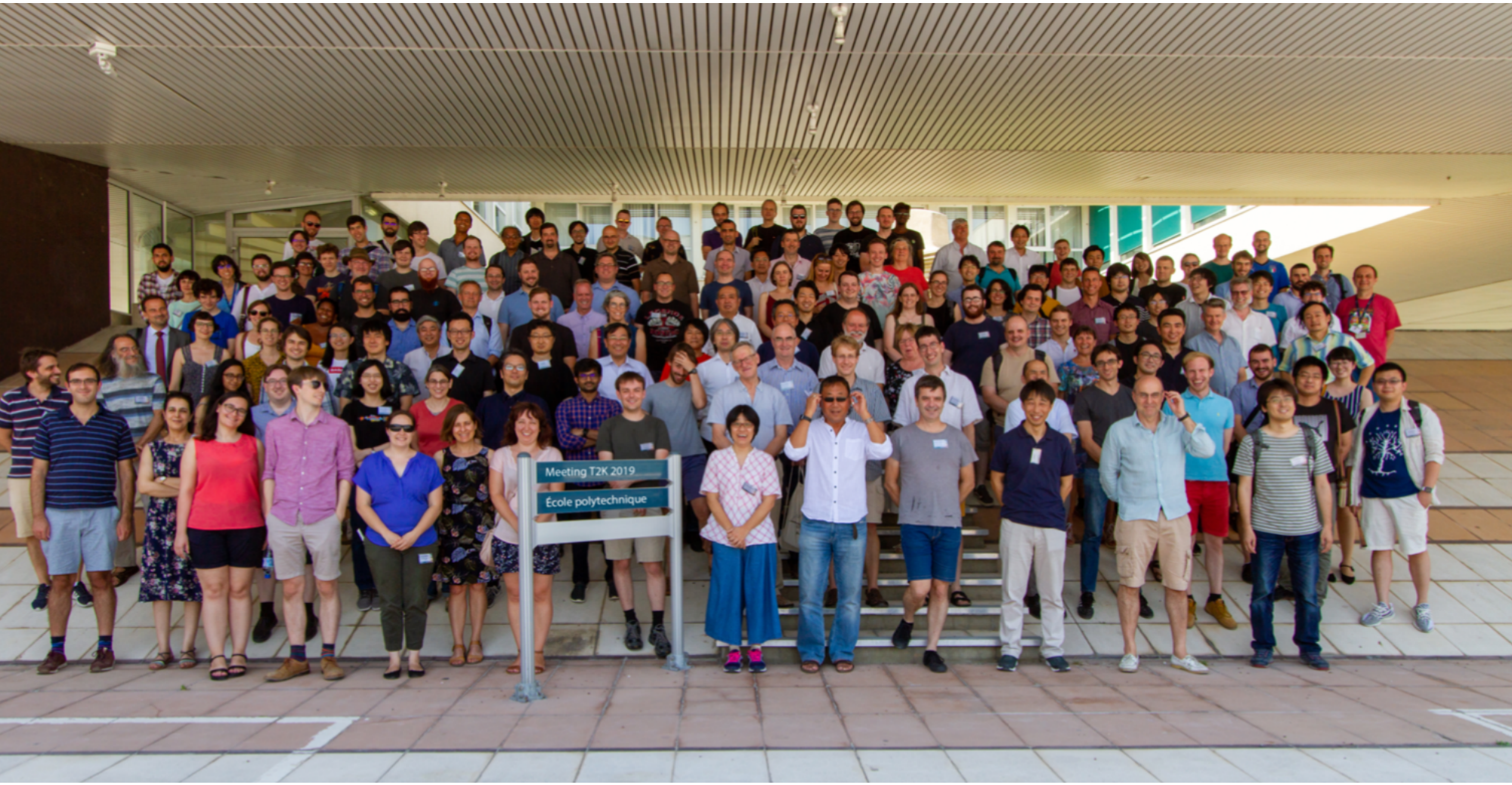
Super-K Sample	pre-ND fit error	post-ND fit error
ν 1 μ-like ring	11.1%	3.0%
$\bar{\nu}$ 1 μ-like ring	11.3%	4.0%
ν 1 e-like ring	13.0%	4.7 %
$\bar{\nu}$ 1 e-like ring	12.1%	5.9%
ν e-like ring +Michel Electron	18.7%	14.3%

Summary

- ND280 studies interactions in our unoscillated beam
- External measurements constrain model before fit
- More sophisticated models allow us to achieve better data consistency
- Extensive validation including multiple fitting techniques
- Strong anti-correlations between flux and cross-section parameters reduce Super-K sample uncertainties (as much as 11.1% to 3.0%)

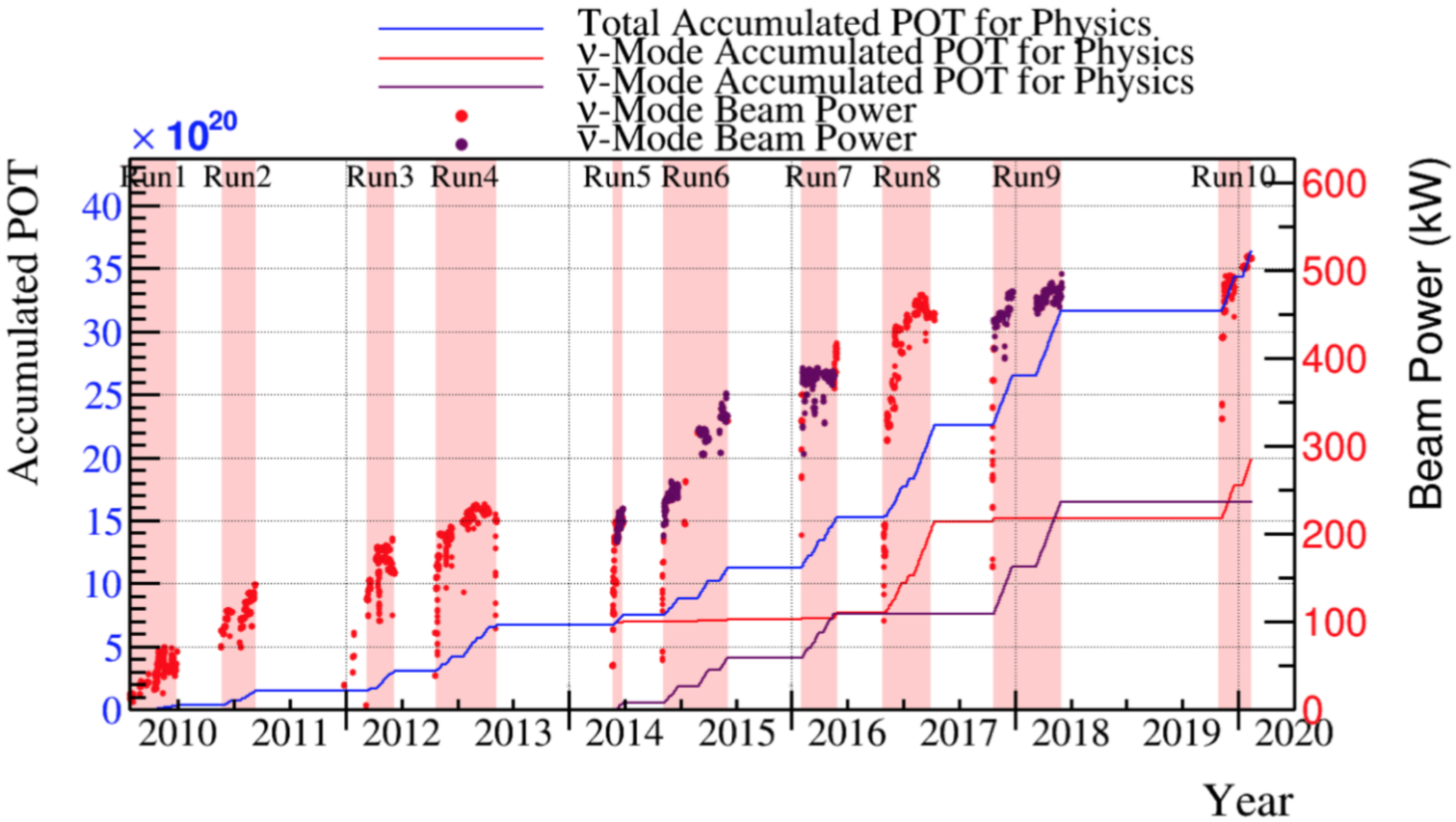


Thank You



BACKUP

New Data



*POT = Protons On Target

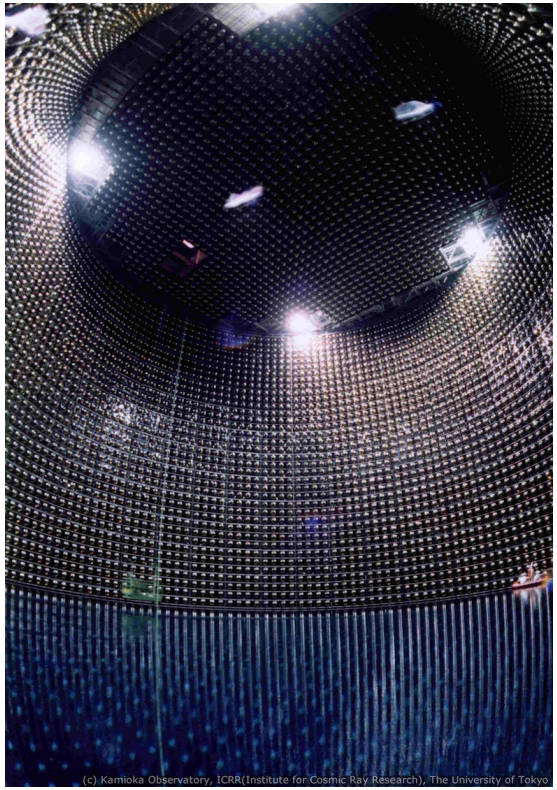
33% increase in ν-mode POT at Super-K and double the POT at ND280 ν-mode POT of 1.97×10^{21} and $\bar{\nu}$-mode POT of 1.63×10^{21}.

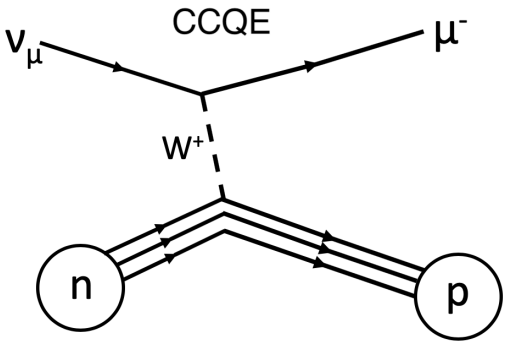
Interaction Model Updates

- CCQE nuclear model RFG→SF
- Lepton momentum shifting nucleon removal energy systematic
- 8 new CCQE normalisation parameters giving freedom in Q^2
- 2p2h energy dependence*
- Low momentum pion $I_{\frac{1}{2}}$ non-resonant single pion production backgrounds for antineutrino interactions*
- More sophisticated Multi-π and DIS treatment including Bodek-Yang corrections
- Correlated near and far detector final state interaction modelling

*Parameters for which we do not have near detector sensitivity are fixed in gradient descent fitter and left free to vary in the MCMC at the near detector.

Super-Kamiokande



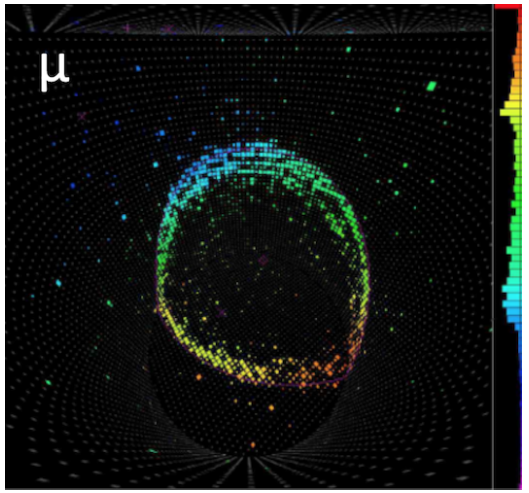


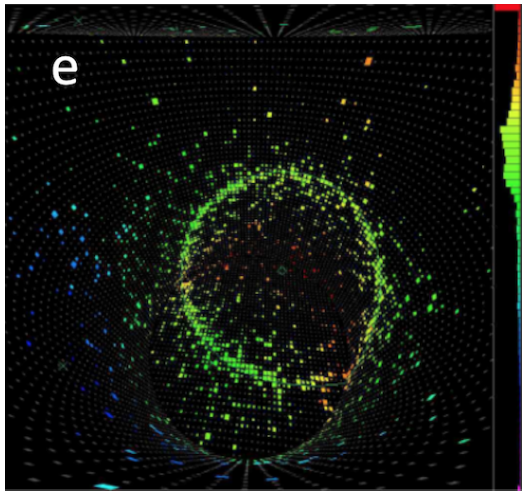
50,000 tonne water Cherenkov detector

11,000 20" inner PMTs, 2,000 8' outer PMT for cosmics/exiting particles

Muons have sharp well defined rings

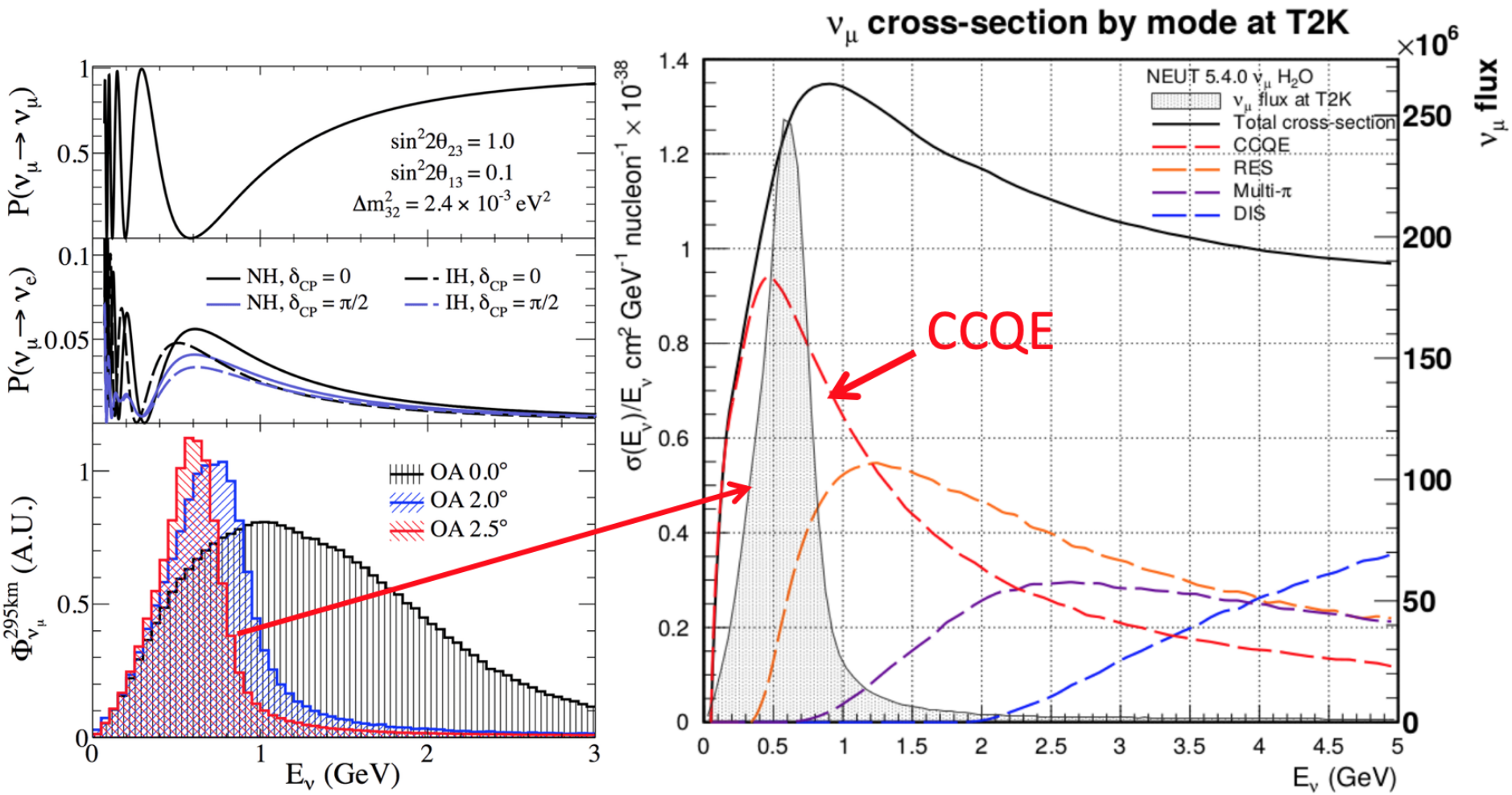
Electrons scatter and make diffuse "fuzzy" rings





Off-Axis "Trick"

We can narrow and enhance our ν beam flux around our desired E_ν.
Super-K is at 2.5° off-axis - 600 MeV peak

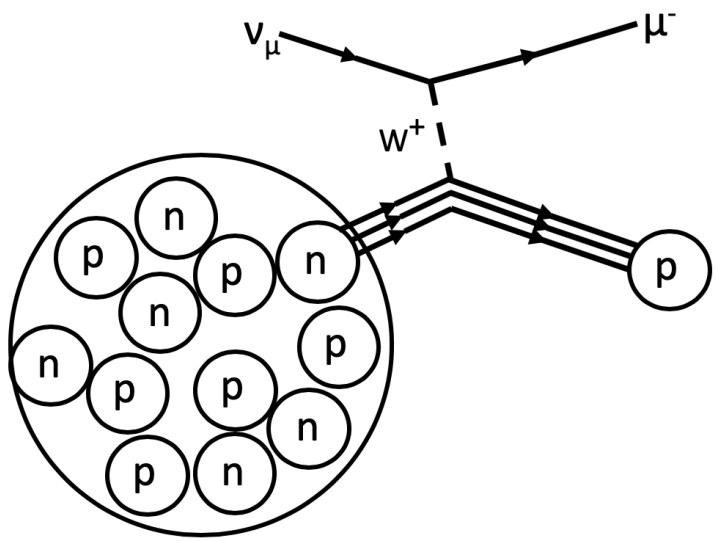


Erec Calculation

Neutrino oscillations are E_ν dependent. We need an observable close to the true E_ν

Reconstruct neutrino from final state charged lepton

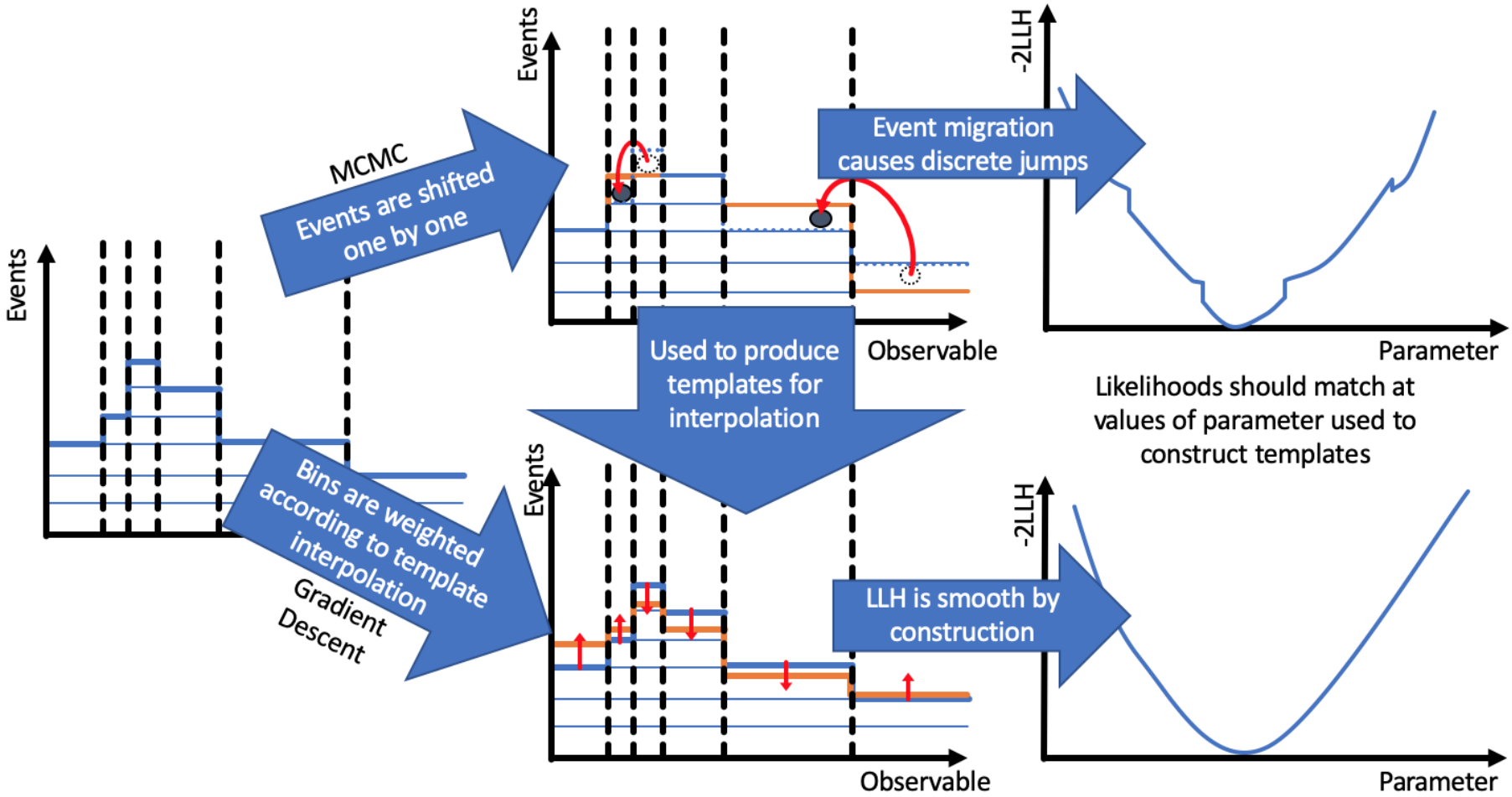
Assuming quasi-elastic scattering from single bound nucleon (CCQE)



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

Removal energy implementation

Variations of nucleon removal energy move events around observable space fitted in (p_μ) which creates discrete jumps in the likelihood as events cross boundaries between bins. This is pathological to the gradient descent fitter so we must make an effective parameter which behaves smoothly.



Fitter bias

By fitting to throws of our model we can evaluate biases in the fitter. We can then produce a bias corrected nominal prediction to see the expected size of the impact on event rates of the near detector samples.

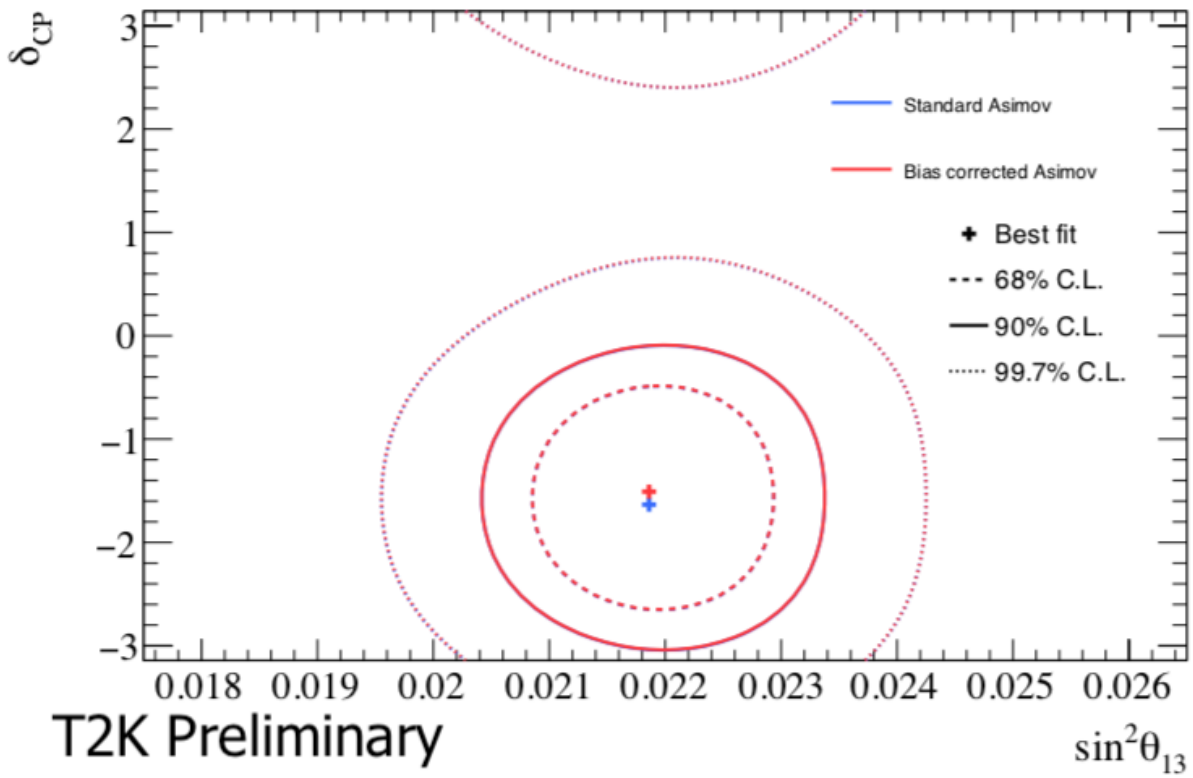
Sample	Nominal	Bias Corrected	Percent change
FHC FGD1 ν_μ CC 0π	27951.8	27534.05	1.49
FHC FGD1 ν_μ CC 1π	8358.62	8149.57	2.50
FHC FGD1 ν_μ CC Other	7031.49	6912.58	1.69
FHC FGD2 ν_μ CC 0π	27558.87	27258.62	1.09
FHC FGD2 ν_μ CC 1π	6723.79	6566.26	2.34
FHC FGD2 ν_μ CC Other	6454.74	6345.15	1.70
RHC FGD1 $\bar{\nu}_\mu$ CC CC 0π	7270.33	7297.51	0.37
RHC FGD1 $\bar{\nu}_\mu$ CC CC 1π	694.32	679.55	2.13
RHC FGD1 $\bar{\nu}_\mu$ CC CC Other	1286.79	1269.30	1.36
RHC FGD2 $\bar{\nu}_\mu$ CC CC 0π	7036.5	7091.23	0.78
RHC FGD2 $\bar{\nu}_\mu$ CC CC 1π	624.69	614.56	1.62
RHC FGD2 $\bar{\nu}_\mu$ CC CC Other	1176.53	1159.12	1.47
RHC FGD1 ν_μ CC 0π	3035.59	2999.02	1.20
RHC FGD1 ν_μ CC 1π	1159.01	1130.24	2.48
RHC FGD1 ν_μ CC Other	1073.13	1053.38	1.84
RHC FGD2 ν_μ CC 0π	3012.4	2975.55	1.22
RHC FGD2 ν_μ CC 1π	930.64	904.85	2.77
RHC FGD2 ν_μ CC Other	1000.39	980.62	1.98
Total	112379.63	110921.14	1.30

Sub 3% effect at ND280.
Smaller than nominal event rate fractional uncertainty.
CC1π samples most affected.

Negligible effect on oscillation parameter contours when propagated to Super-K.

ND280 fit bias impact at SK

What impact would these biases have on the oscillation parameter extraction?



Only shows up in I.H. $\delta_{CP}, \sin^2\theta_{13}$ best fit point. No visible difference in contours. For some known values of the model parameters (Not Data) What

Does our model describe our data well?

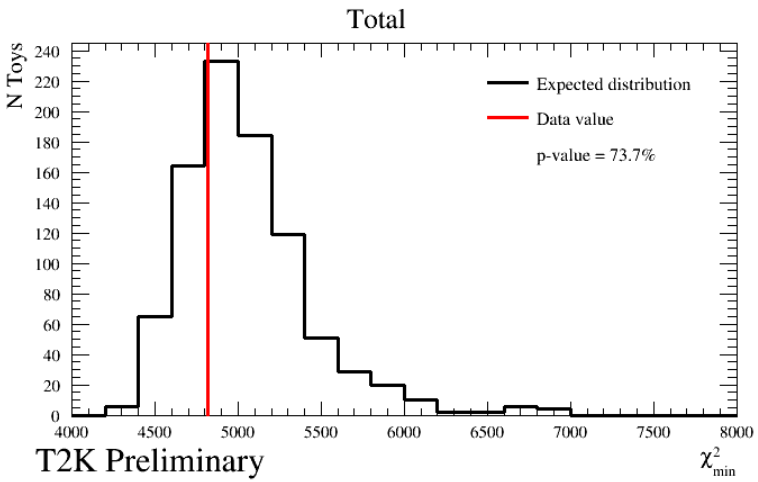
Calculating a p-value

By calculating a p-value for our near detector best fit, we can test the ability of our model to cover the region of phase space which best describes our data.

"Toy" data sets are thrown from prior covariance and the nominal model is fit to each toy.

The fraction of fits with a χ^2_{min} greater than that of the data, and therefor less likely than the data given our model, is the p-value.

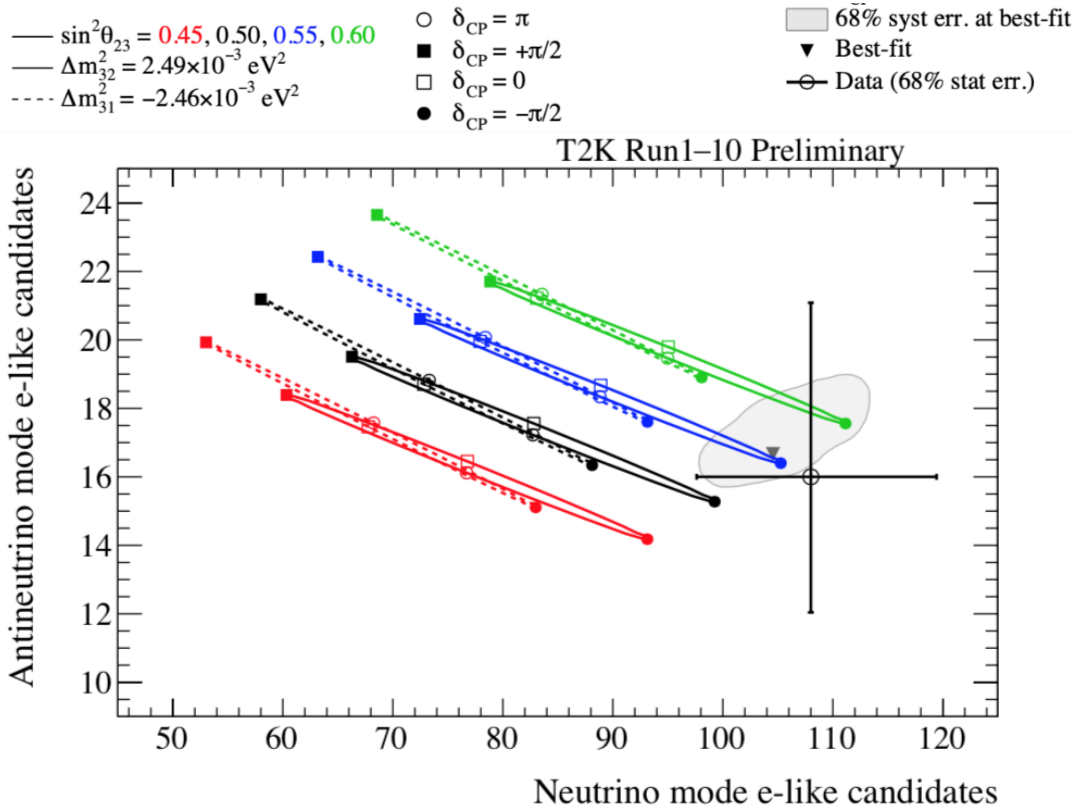
From this we calculate $p = 74\%$ which is an improvement on previous value (2018) $p = 50\%$

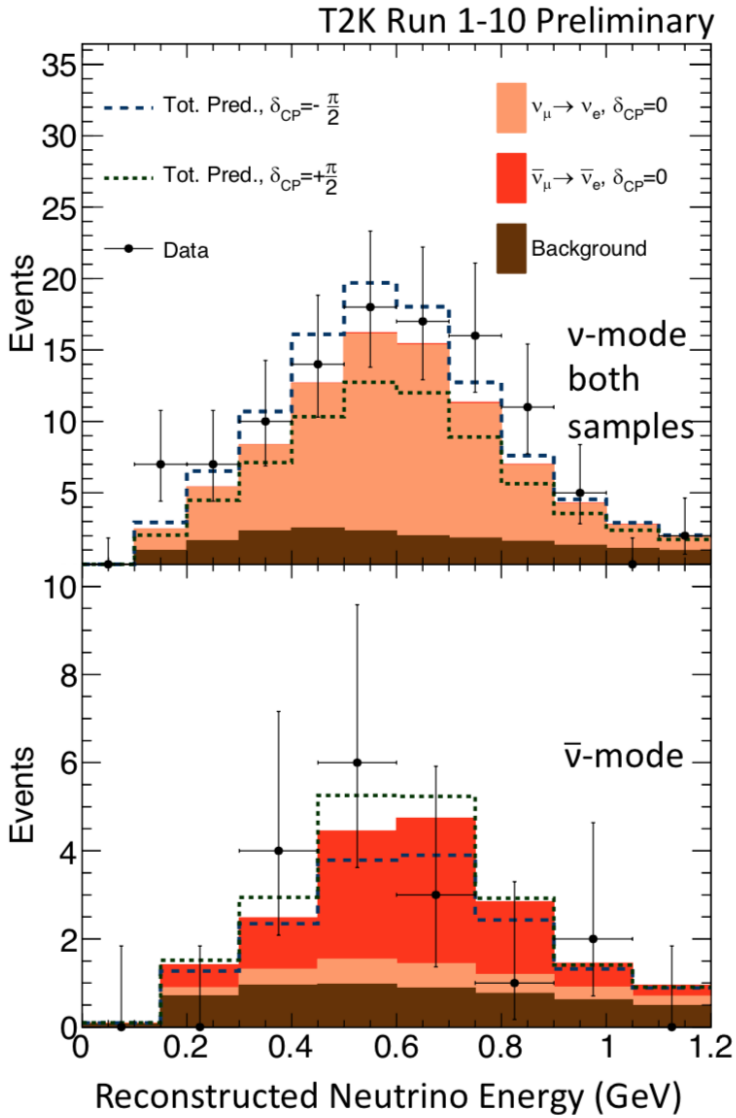


Super-K Data and PMNS Predictions

We see an **excess of electron neutrinos** when compared to CP conserving case.

Suggests preference for
$\delta_{CP} = -\frac{\pi}{2}$ and **Normal Ordered** masses

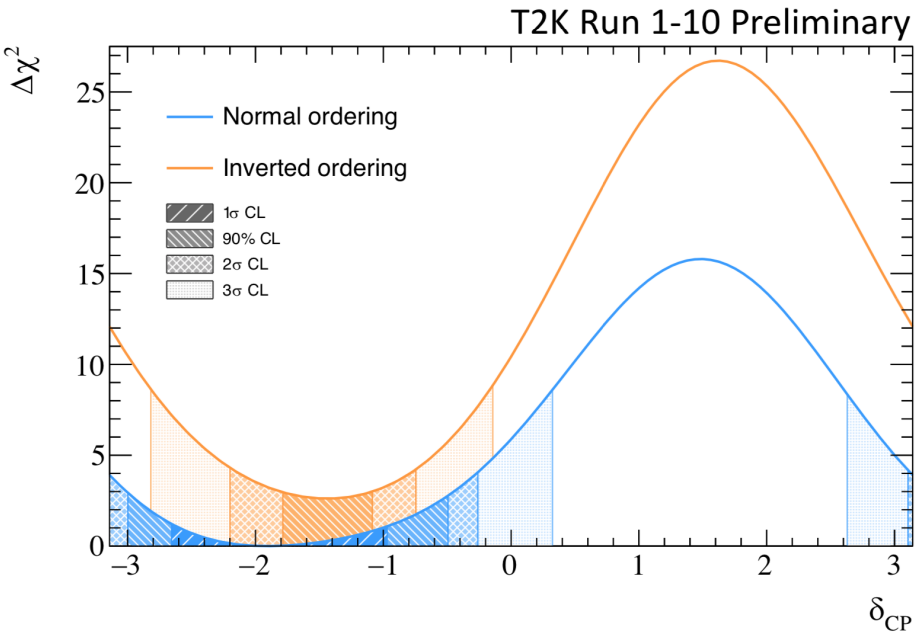




δ_{CP} Constraints

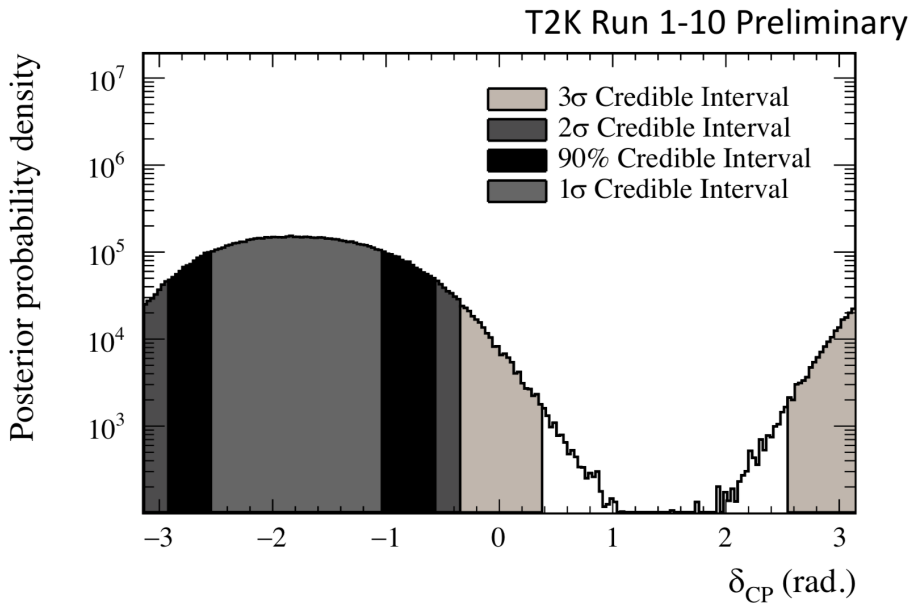
Frequentist $\Delta\chi^2$

Feldman-Cousins corrected



Bayesian posterior probability density

Marginalized over mass hierarchies.

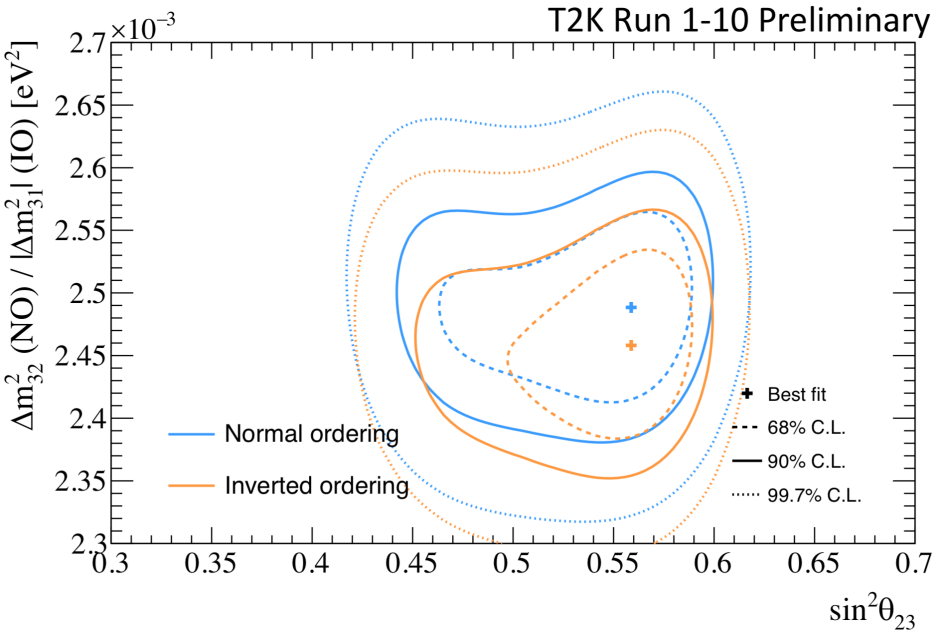


CP conserving values $(0,\pi)$ excluded at 90% but π not quite at 2σ

35% of all values excluded at 3σ when marginalised over both hierarchies

Alternative model robustness studies show largest $\Delta\chi^2$ change would cause left (right) edge of 90% interval to move by 0.073 (0.080)

Atmospheric parameters



Preference for upper octant of θ_{23} and normal ordered neutrino masses.

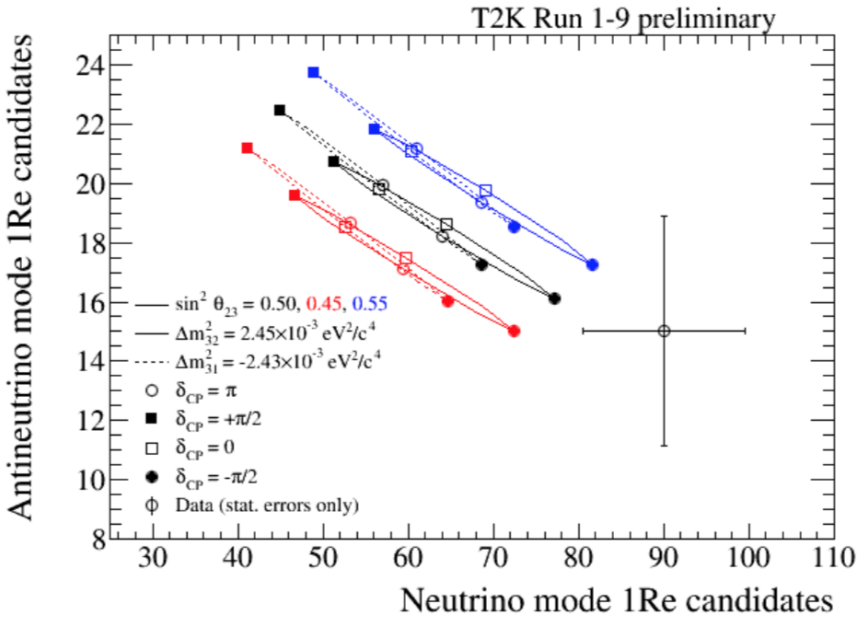
Slight preference for non-maximal $\sin^2\theta_{23}$

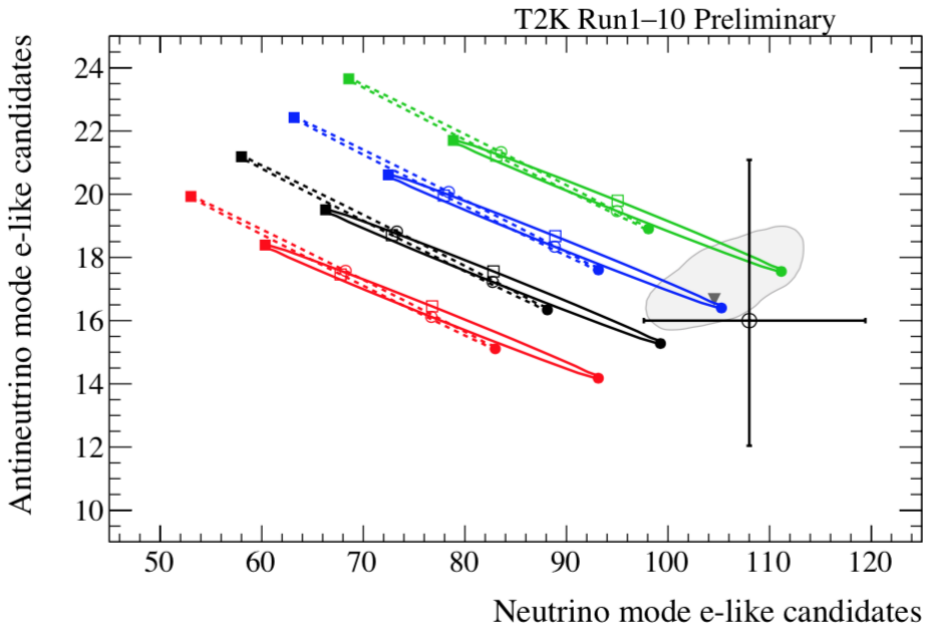
Posterior Probabilities

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IO ($\Delta m^2_{32} > 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

Comparison to Run 1-9 results

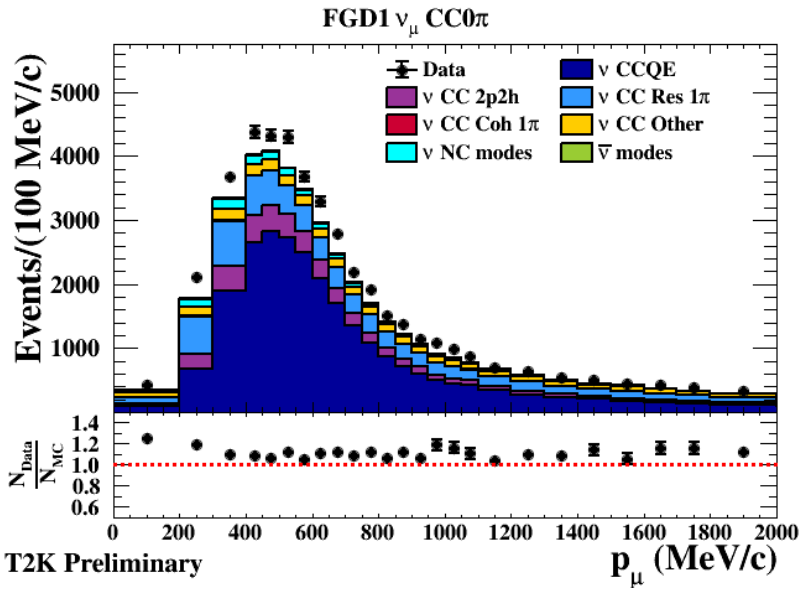
Previous result was far more non-PMNS like due to excess of neutrinos. This excess has reduced with addition of statistics.

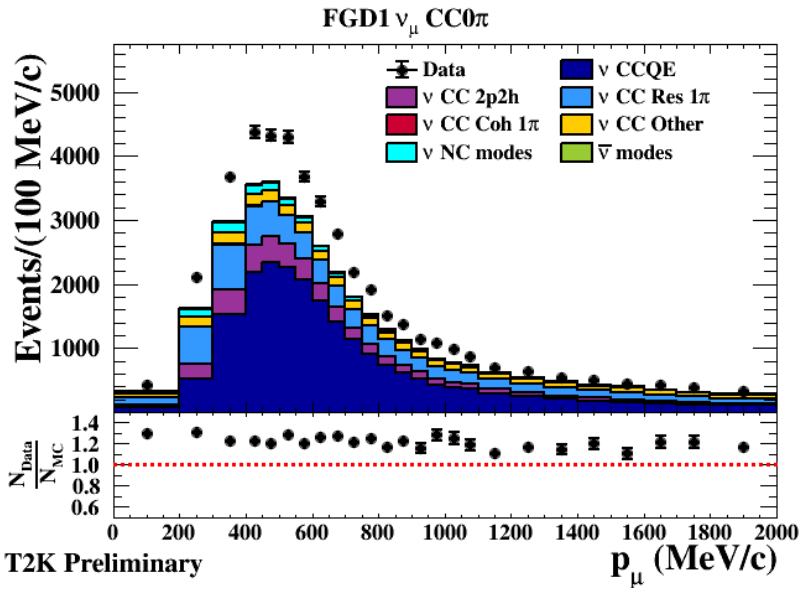




Impact of priors on prefit prediction

Effect of externally motivated priors on parameters giving Q^2 freedom to CCQE events on ND280 FGD1 CC0π sample





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