The Role of Cross Sections in the Oscillation Analysis: The T2K Experience

Clarence Wret
On behalf of the T2K collaboration

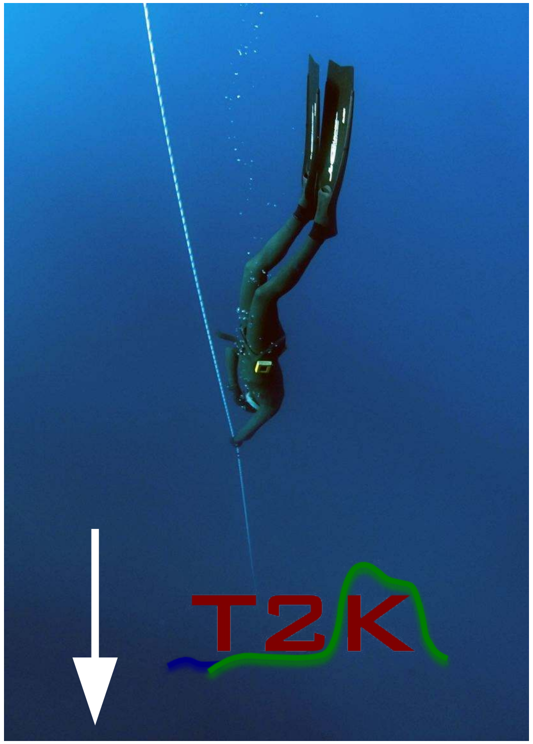
UNIVERSITY of ROCHESTER

T2K

NuFact 2018, 17 August 2018
Virginia Tech, Blacksburg

Disclaimer

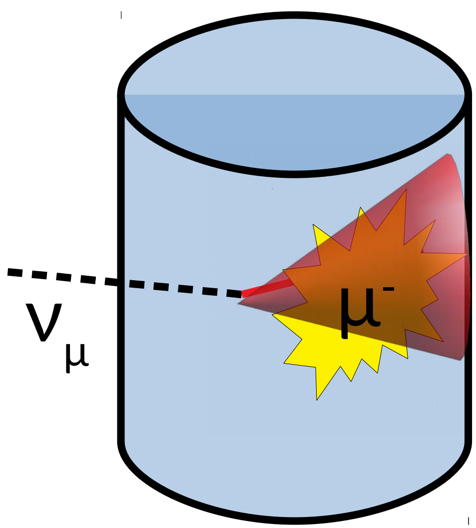
- Not mentioning the T2K detectors here or any detailed results
  - *Cross Section Results from T2K*, C. Wret, Mon. 5pm
  - *Results and Prospects from T2K*, S. Dennis, Tue. 11Am
  - *Recent Results from the T2K Near Detector*, X. Lu, Wed. 10am
  - *Details of the T2K oscillation analyses*, D. Sgalaberna, Thu. 2.30pm



- There's plenty of air for everyone!

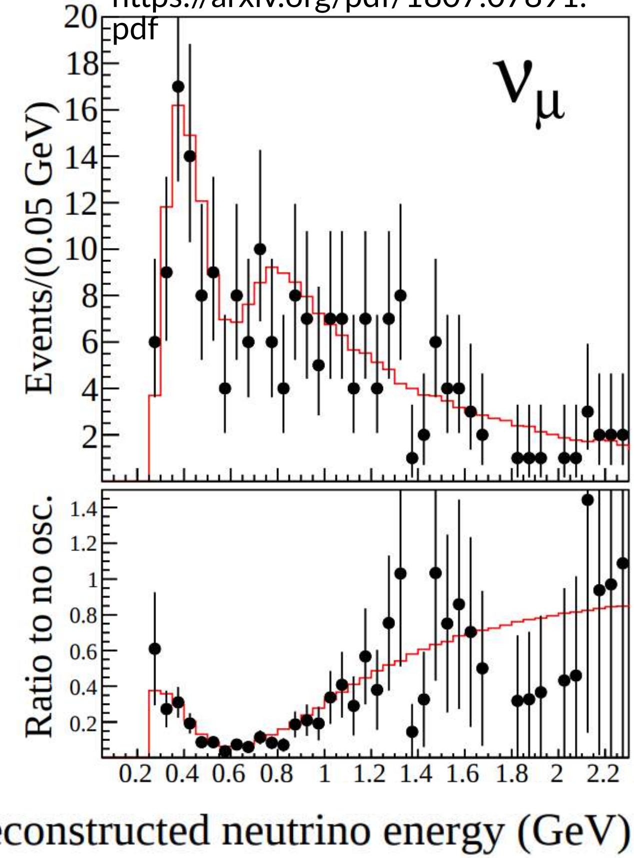
Measuring oscillations

- T2K-SK selections are currently all 1 ring μ/e
- Use measured lepton information to reconstructed E_ν^{CCQE}
  - Assumes CCQE interaction and stationary nucleon
  - Inherent bias from missing energy and initial state motion
    - e.g. Spectral Function, 2p2h, FSI
    - Biases accounted for in model
    - Unknown biases: aye there's the rub!



$$E_\nu^{CCQE} = \frac{m_f^2 - (m_i')^2 - m_l^2 + 2m_i' E_l}{2(m_i' - E_l + p_l \cos\theta_l)}$$

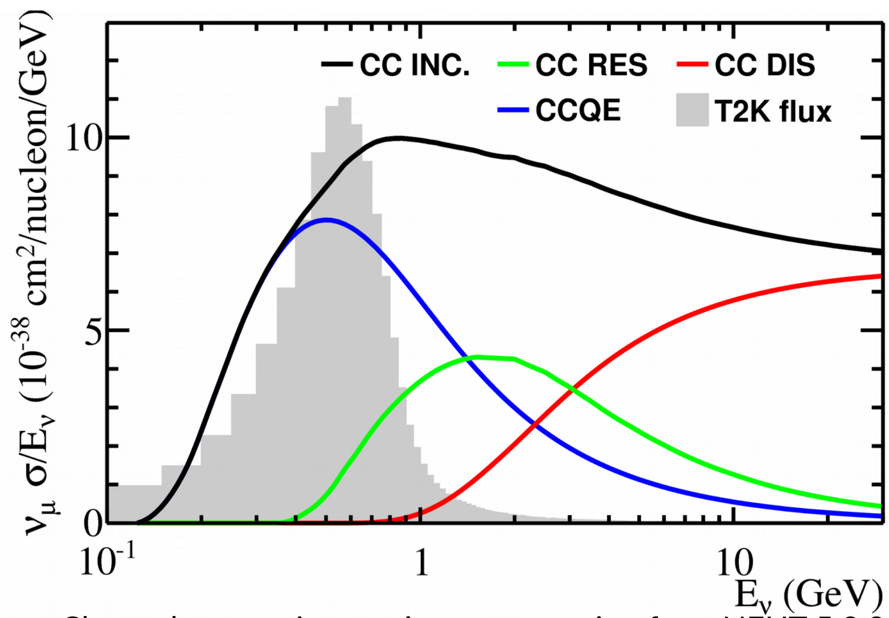
T2K August 2018, https://arxiv.org/pdf/1807.07891.pdf



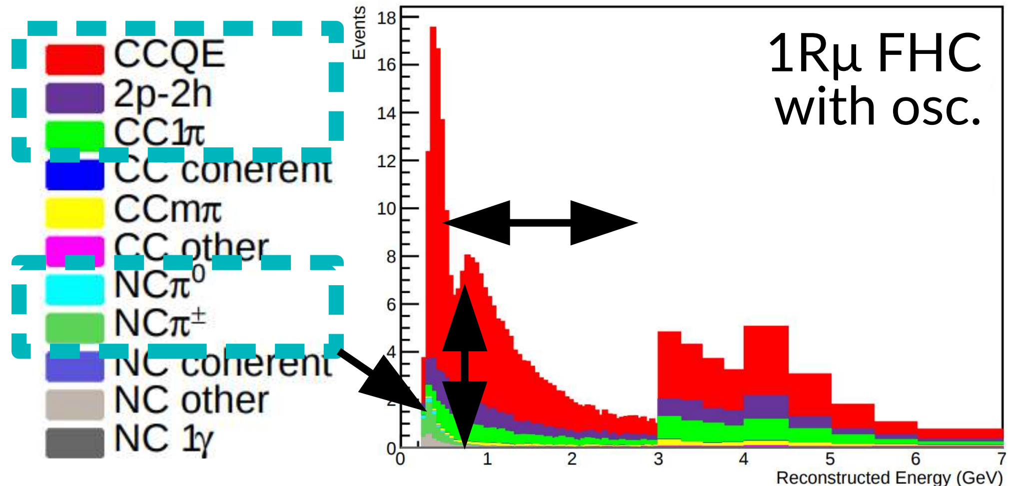
UNIVERSITY of ROCHESTER

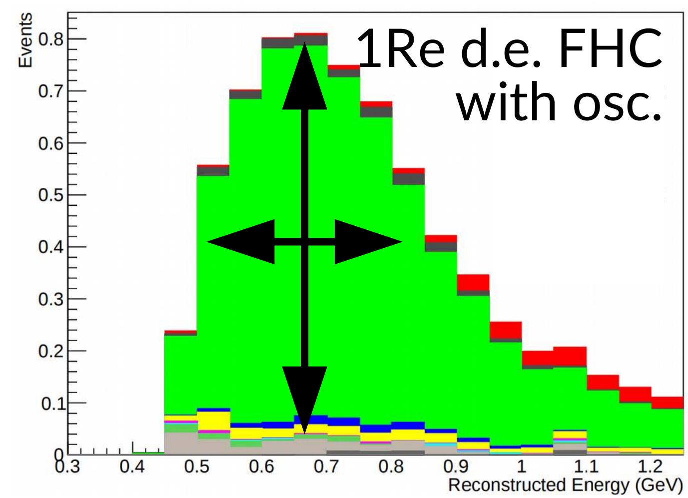
Measuring oscillations

- T2K-SK 1 ring selections emphasise modelling the 0π final state
  - CCQE, 2p2h, single pion + abs.



Charged current interaction cross section from NEUT 5.3.2





- 2017 analysis included 1 ring e + 1 decay *e*
  - Explicitly selecting single pion events below Cherenkov threshold
- Interaction modelling changes 1) amplitude of prediction and 2) shifts the oscillation dip in E_ν: **affects both mixing angle and mass squared**

Measuring oscillations

$$R(\vec{\mathbf{x}}) = \overbrace{\Phi(E_\nu) \times \boxed{\sigma(E_\nu, \vec{\mathbf{x}})} \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(\nu_A \rightarrow \nu_B)$$

$$\underbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(\nu_A \rightarrow \nu_B)}_{\text{Far}}$$

- Modelling relates observables (e.g. p_μ θ_μ) to neutrino energy, E_ν, which determines the oscillation parameters
- Near and far detectors don't cancel systematics perfectly
  - E_ν spectrum is different in the far detector
  - Acceptance, efficiency and targets differs in the detectors
- Data predominantly from ν_μ: model used to predict ν_e from ν_μ
- Require few percent cross section systematics in current and future oscillation experiments
- <u>*WG2 Goals for the Meeting*, K. Niewczas, Mon. 11.15am</u>

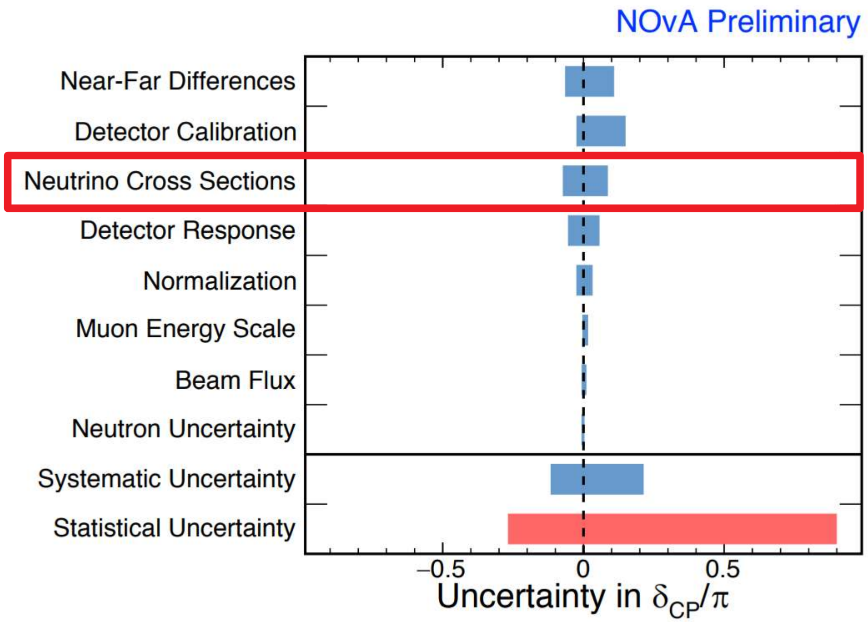
Snapshot of current impact

- Large systematics at T2K and NOvA long-baseline oscillation experiments

Effect on ΔN/N at Super-Kamiokande

Source [%]	ν_μ	ν_e	$\nu_e\pi^+$	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	2.4	7.8	4.1	1.7	4.8
Flux & ND280-constrained cross sec.	3.3	3.2	4.1	2.7	2.9
SK detector systematics	2.4	2.9	13.3	2.0	3.8
Hadronic re-interactions	2.2	3.0	11.5	2.0	2.3
Total	5.1	8.8	18.4	4.3	7.1

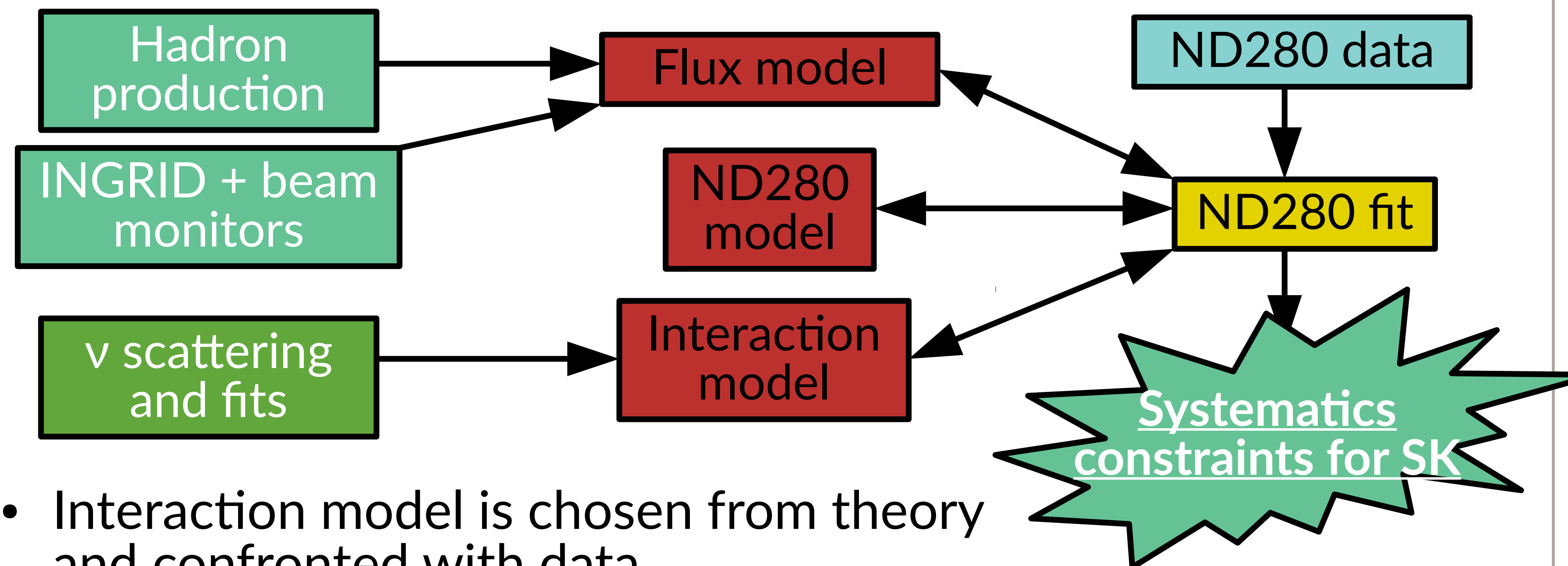
T2K August 2018, https://arxiv.org/pdf/1807.07891.pdf



NOvA Wine and Cheese, A. Himmel, June 15, 2018

- NOvA's detector calibrations makes neutrino interactions dominant systematic for atmospheric and δ_{CP} parameters in future
  - *Details of the NOvA oscillation analyses*, E. Smith, Thu. 2pm
  - *Details of the T2K oscillation analyses*, D. Sgalaberna, Thu. 2.30pm
  - *NOvA Cross Section Model / Oscillation Needs*, J. Wolcott, Fri. 2pm

T2K oscillation analysis chain



- Interaction model is chosen from theory and confronted with data
- Free parameters subjected to reasonable constraints (see later slides)
  - Compare to external data, inflate uncertainty if necessary
- Fit the model to ND280 data
  - 60,000 CC-inclusive events, split by FGD, topology and neutrino/anti-neutrino: 14 selections*, binned in p_μ $\cos\theta_\mu$
- Parameter constraints on entire model with correlations

Full param. in backups

*Next gen: 120,000+ events, 18 selections

Evaluating the ND280 fit

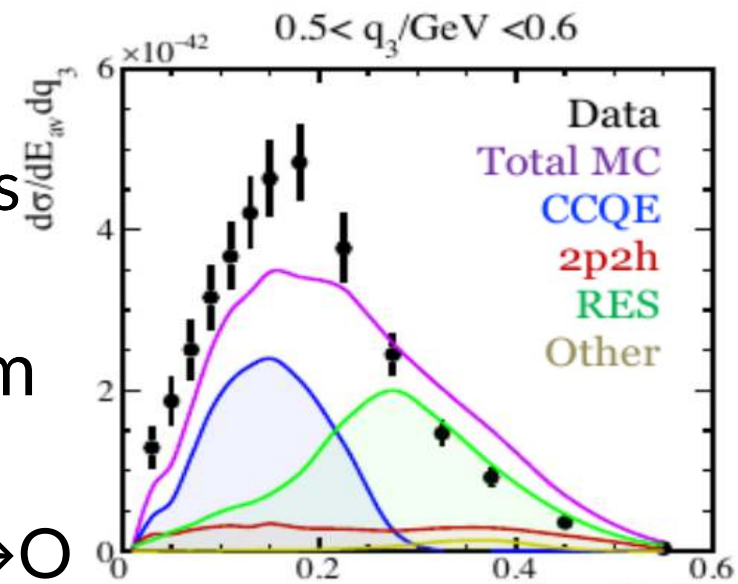
- Important to have full control over systematics parameterisation
  - Feel confident with the 1σ before the fit: weight of the prior
  - Evaluate interaction model against a wide range of data before fitting
- Fitting to ND280 data can expose weaknesses in model
  - Constraints from MiniBooNE, MINERvA or ANL and BNL may be incompatible with T2K results!

Review of Tension in Data/Models of Neutrino Cross Sections, K. Mahn, Wed. 9am

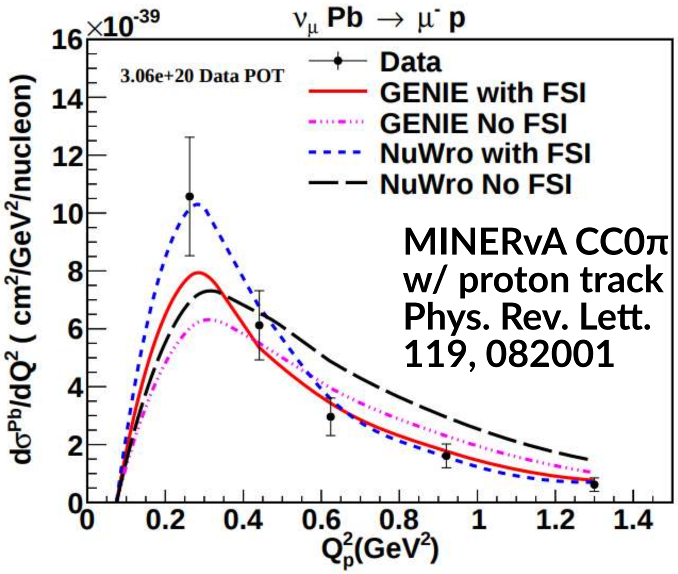
- Fit fully correlates the flux and cross section systematics: correlated uncert.
- P-value from the fit evaluates the goodness of the model before doing OA
  - If it's bad, start again! Think more! Scratch heads!
- Possibility of over-fitting to selected distributions
  - Modelling p_μ $\cos\theta_\mu$ well does not ensure hadronic variables are OK!
  - But (for now) SK only looks at lepton candidate
  - Hadronic variables of interest in the future: ND280 will have to follow

Measurements that make us think

- MINERvA CC-inclusive
  - 2p2h is real but not necessarily Nieves



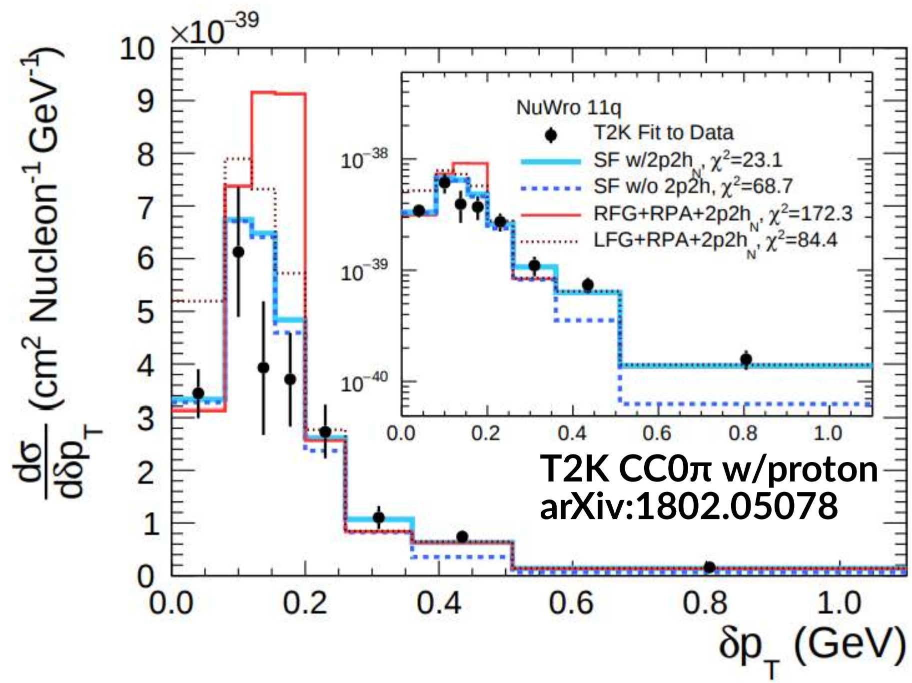
MINERvA CC-inclusve
Phys. Rev. Lett. 116, 071802



MINERvA CC0π
w/ proton track
Phys. Rev. Lett.
119, 082001

- Proton momentum measurements
  - A scaling for C→O

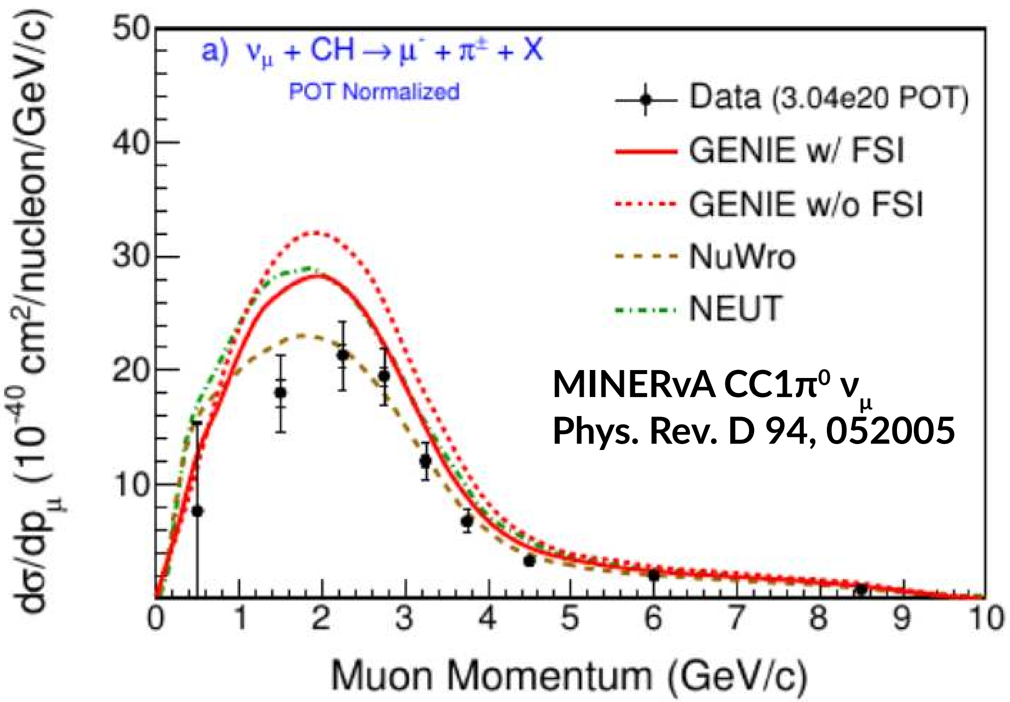
- Transverse variables
  - Sophisticated nuclear effects are a better description of data

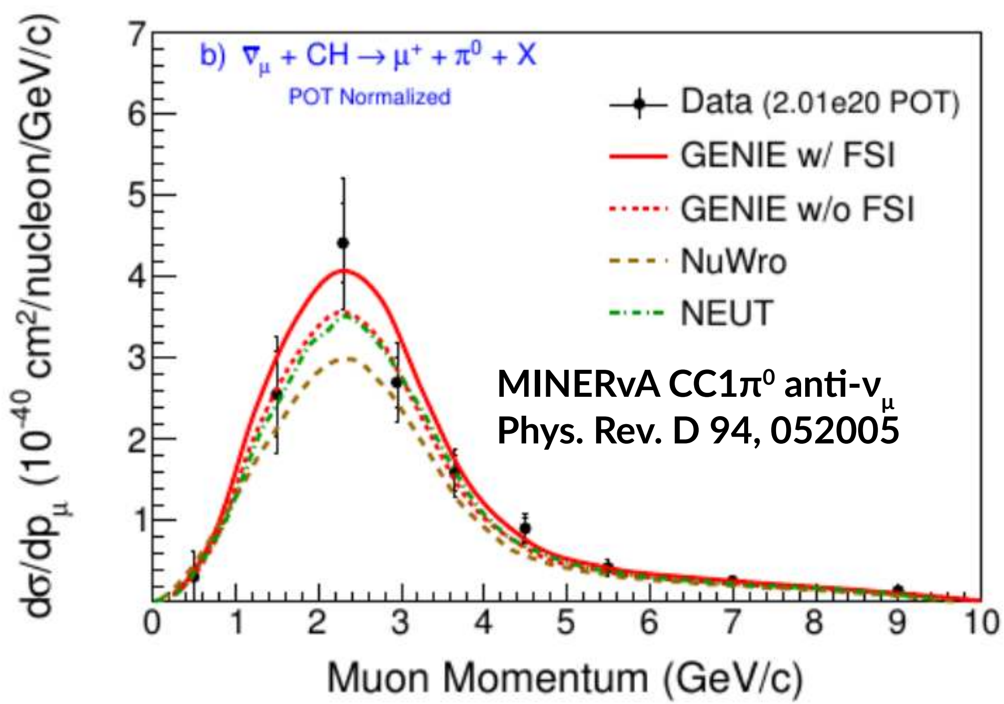


T2K CC0π w/proton
arXiv:1802.05078

Measurements that make us think

- Single pion production
  - No generator or calculation describes T2K, MiniBooNE and MINERvA data at the same time
  - You're very successful if you get CC1π^+ and CC1π^0, or ν_μ and anti-ν_μ, correct!

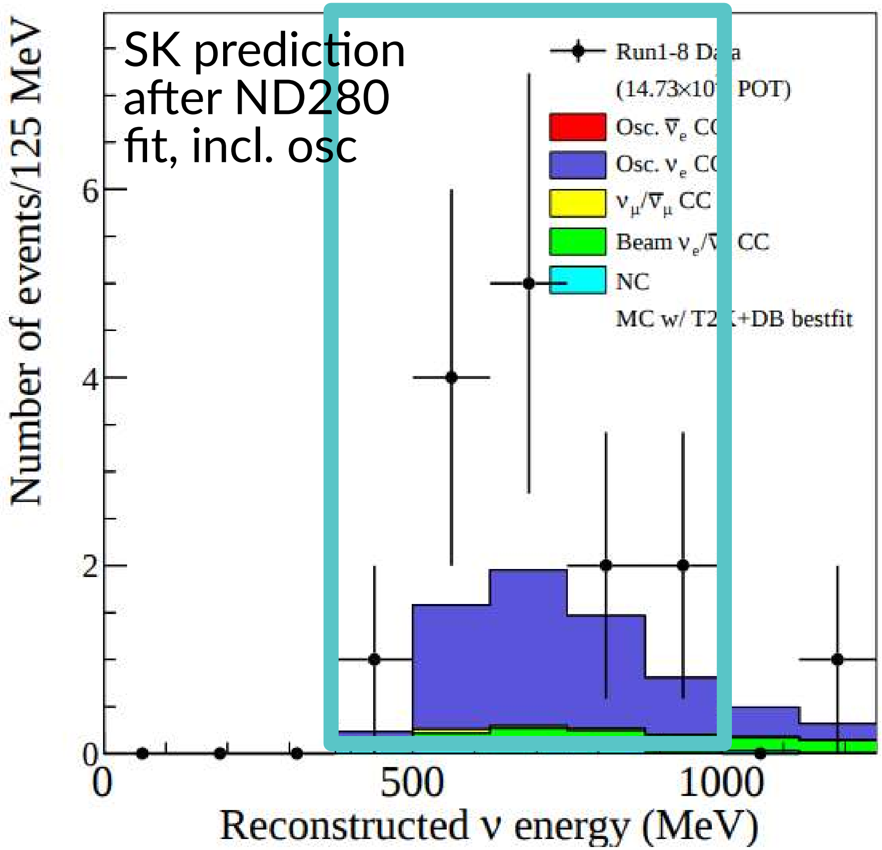


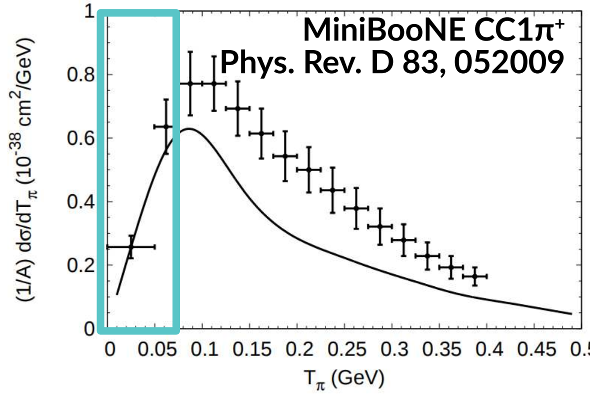


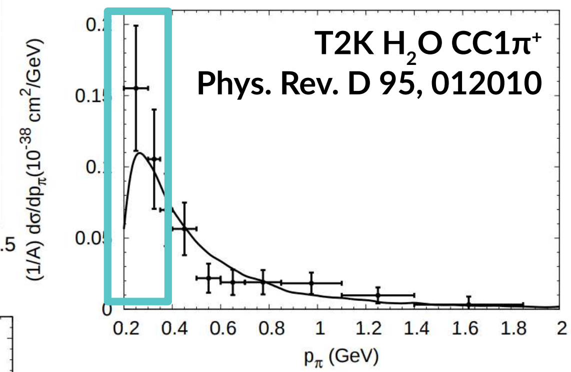
- But where is it from? Nucleon model? Nuclear effect? FSI?
  - Current kinematic distributions don't really shine light, need to look beyond momentum and angle?

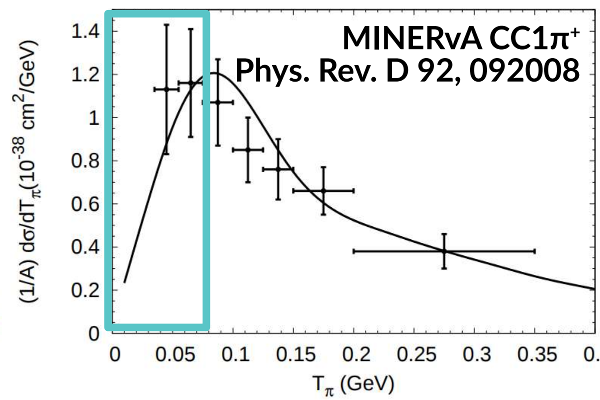
Measurements that make us think

- T2K-SK 1 ring *e* with decay *e* poor MC prediction after ND280 fit









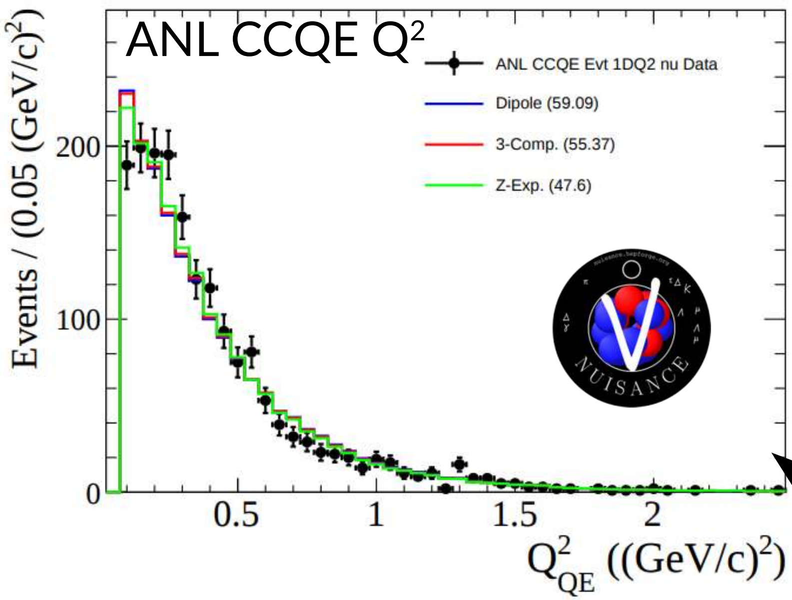
GiBUU, Phys. Rev. C 96, 015503

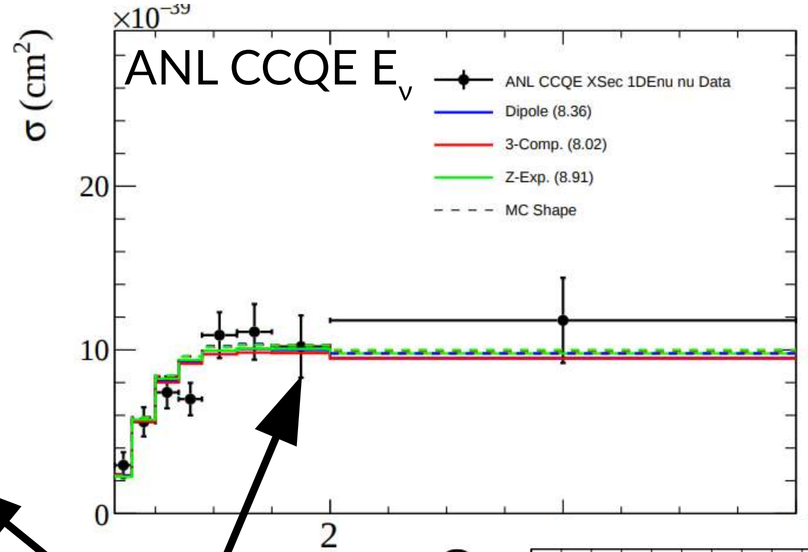
- Low momentum pions are difficult! MINERvA and T2K consistently underpredicted, but MiniBooNE well predicted by GiBUU
- No external ν_e CC1$\pi^{\pm}$ interaction data

- Avoid pion samples at SK until understood? Loss of statistics!

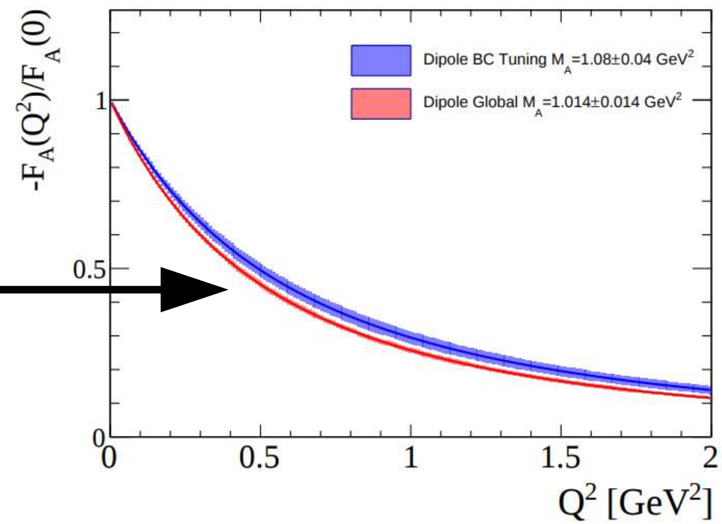
External constraints, CC0π

- M_A^{QE} is initially set to 1.2 GeV/c², but entirely free in ND280 fit
  - Fitting to corrected ANL, BNL, FNAL data, M_A^{QE} = 1.08 ± 0.04 GeV
  - Also fit alternative form-factors, z-expansion and three component





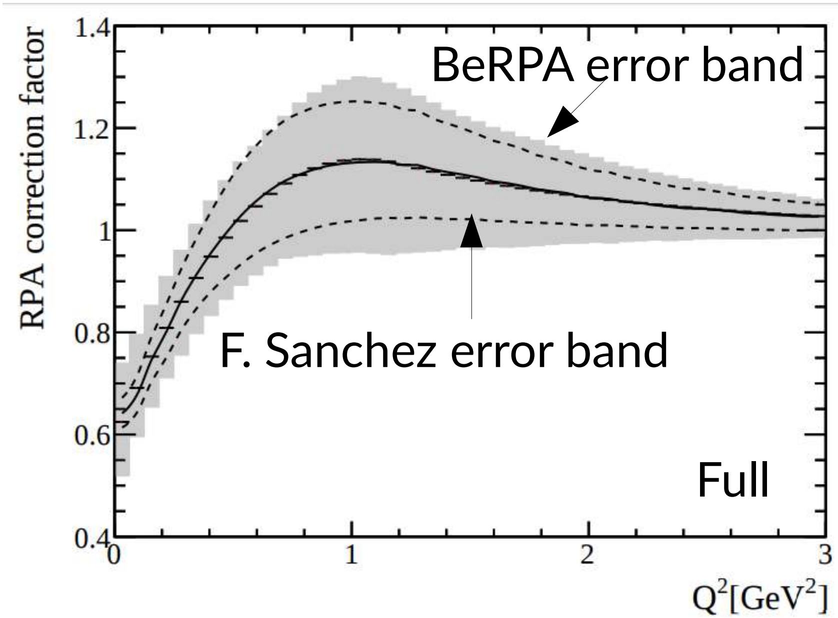
- Z-expansion and three-component better fit than dipole
- Error band for z-expansion is ~constant with Q²: not the case for dipole

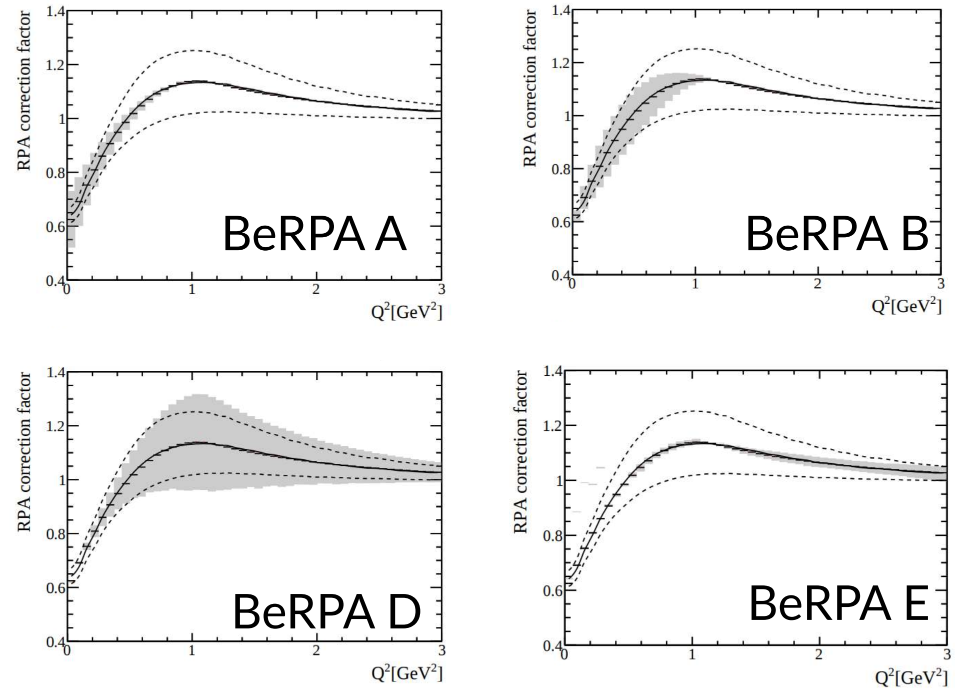


External constraints, CC0π

Phys. Rev. D 88, 113007

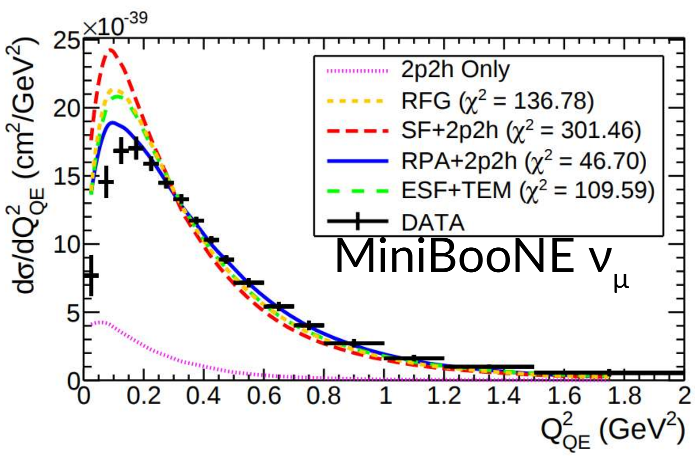
- 5 RPA parameters constrained by the 1σ band from F. Sanchez

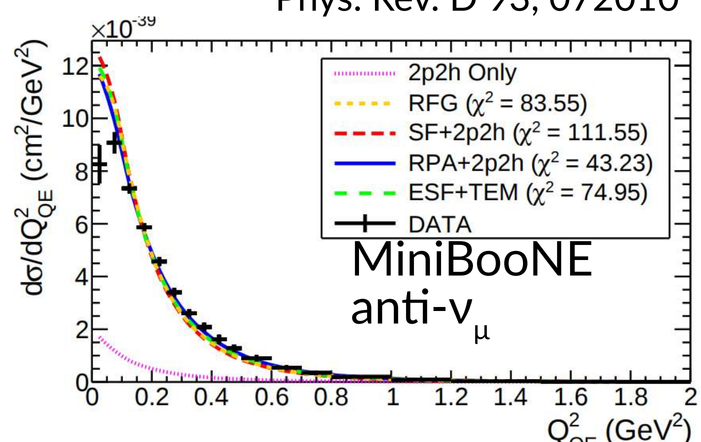




- RFG chosen over SF (Benhar)
  - Fit to MiniBooNE and MINERvA data

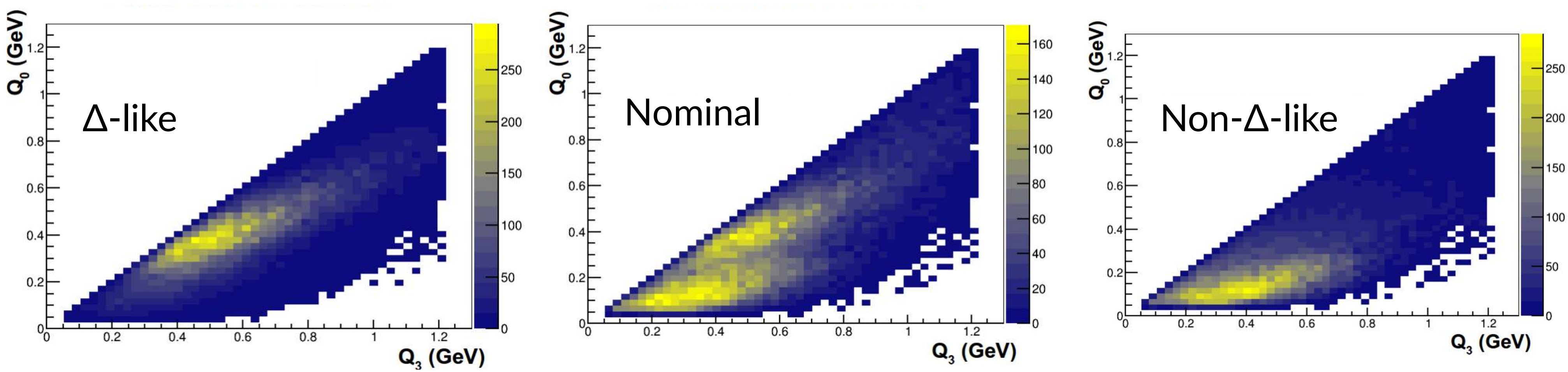
Phys. Rev. D 93, 072010



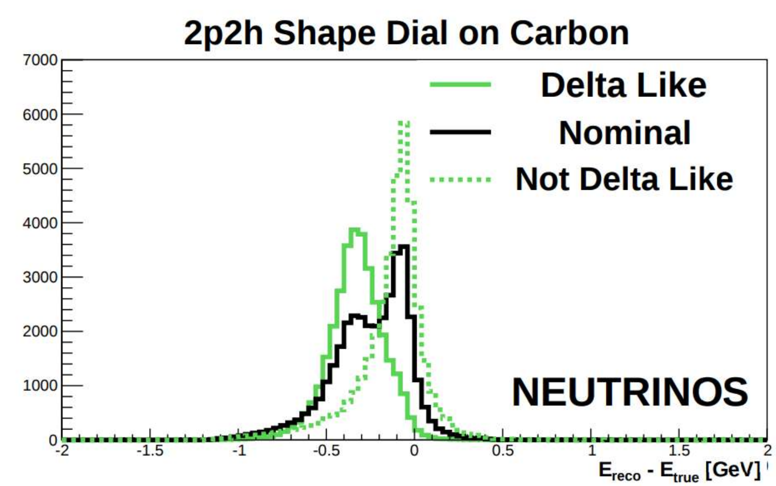


External constraints, 2p2h

- 2p2h shape parameter puts the 2p2h as Delta-like or non-Delta like in Nieves model
  - Separated for Carbon and Oxygen and correlated 30%

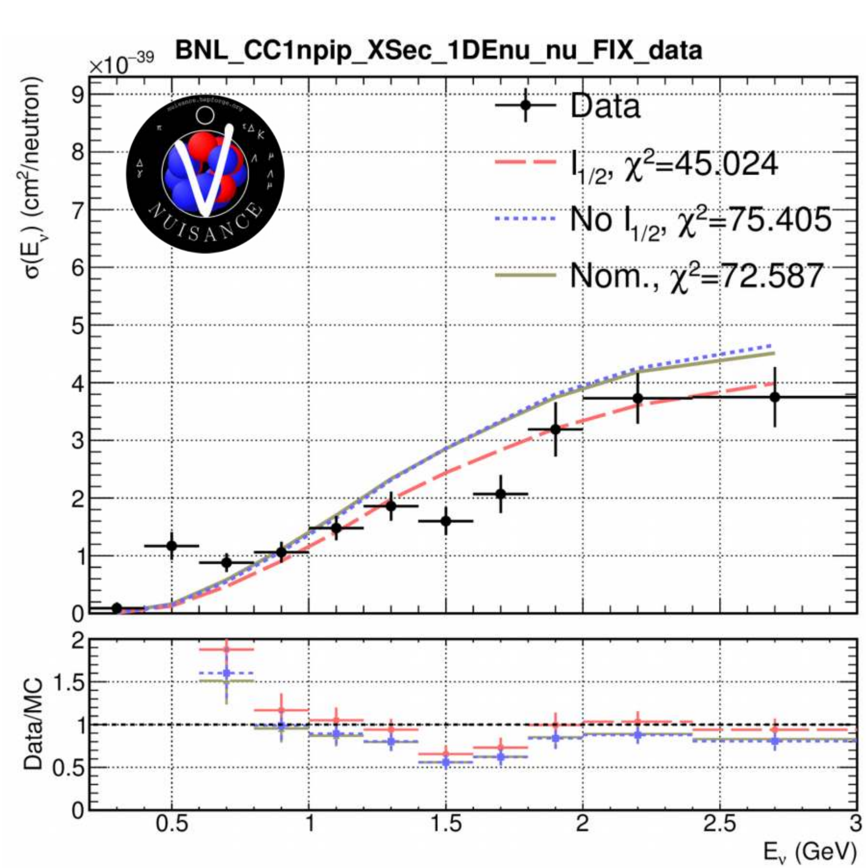


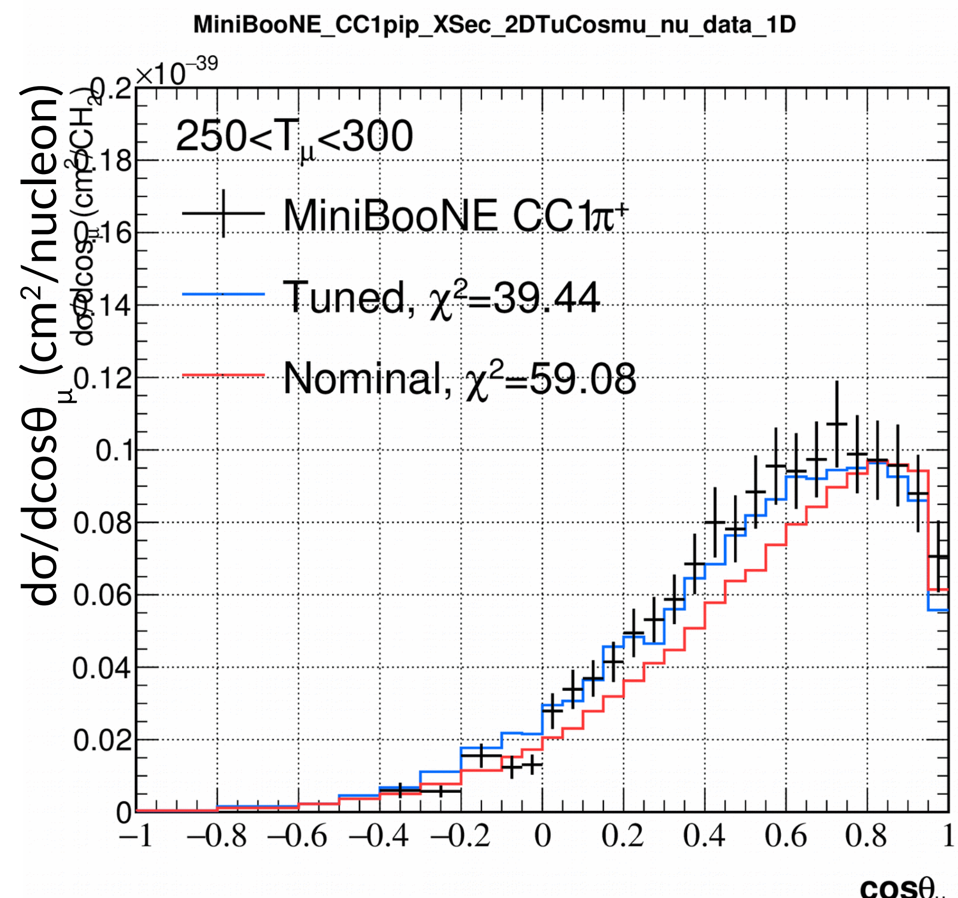
- 2p2h normalisation parameters for ν and anti-ν
- Constrained 2p2h C→O extrapolation normalisation parameter: 30% uncertainty
- No constraints from external data



External constraints, CC1π

- Rein-Sehgal tuned to nucleon data* in all channels, W < 2.0 GeV
  - Cross-checked against FNAL and GGM, and the W < 1.4 and W < 1.6 GeV data
  - Parameter inflation to roughly cover predictions for MiniBooNE and MINERvA in muon variables

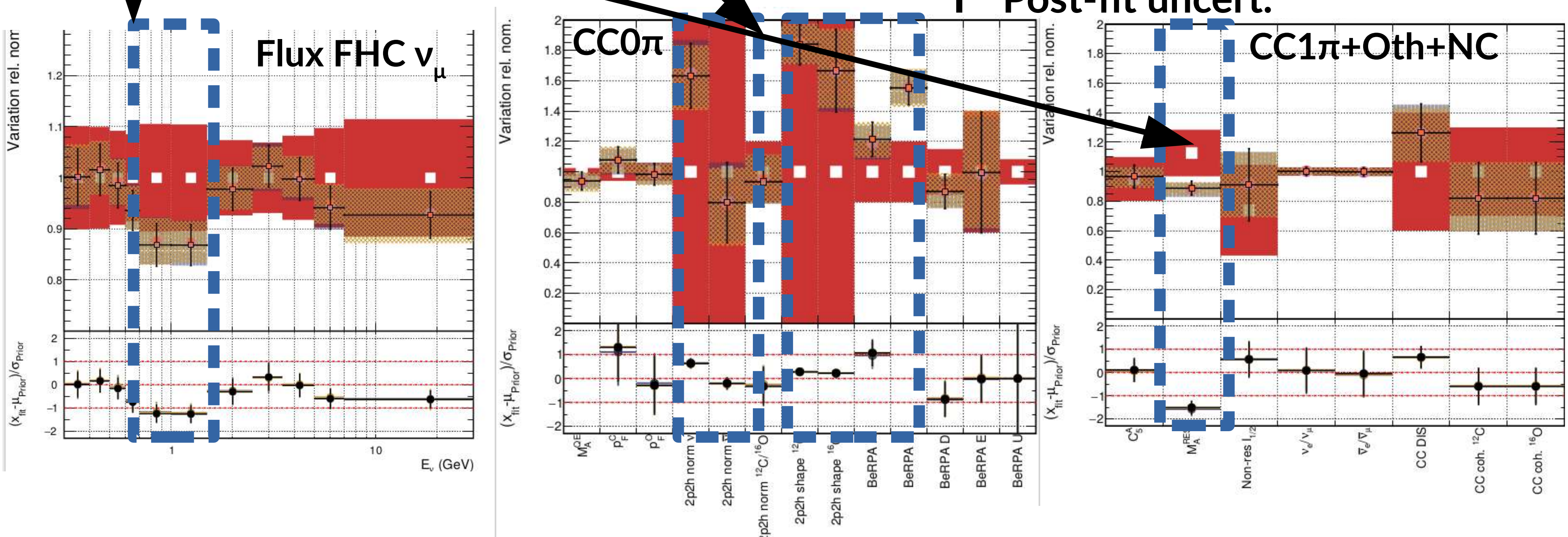




*ANL, BNL correction in Phys. Rev. D 90, 112017

The near detector fit

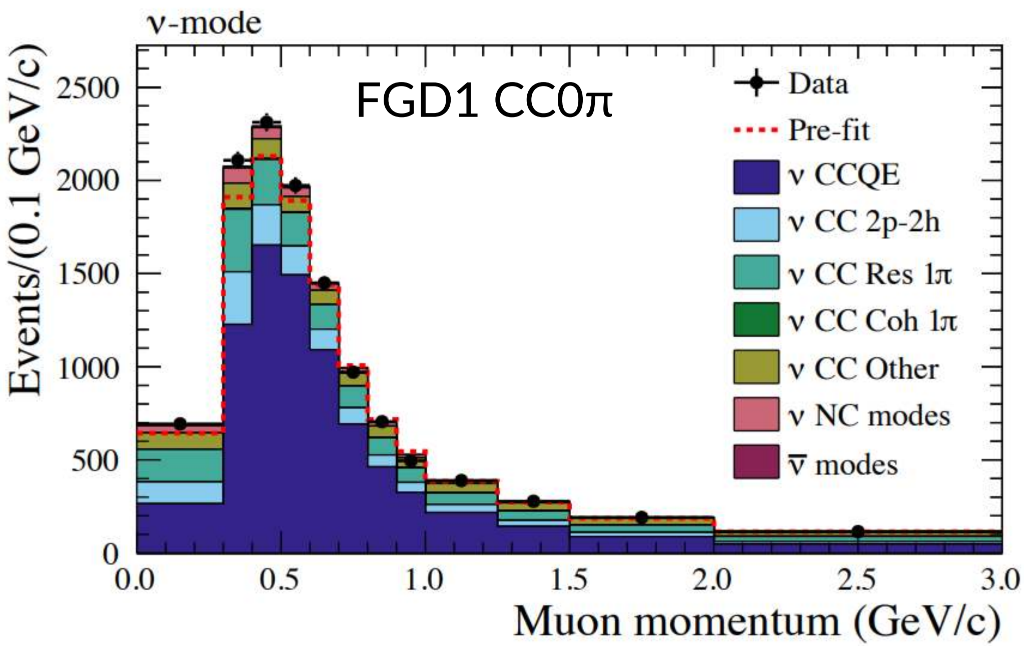
- ~1 GeV flux pulled to 0.9
- BeRPA A and B pulled outside priors, 2p2h shape pushed to boundary, 2p2h normalisation different for ν and anti-ν
- Much lower M_A^{RES}

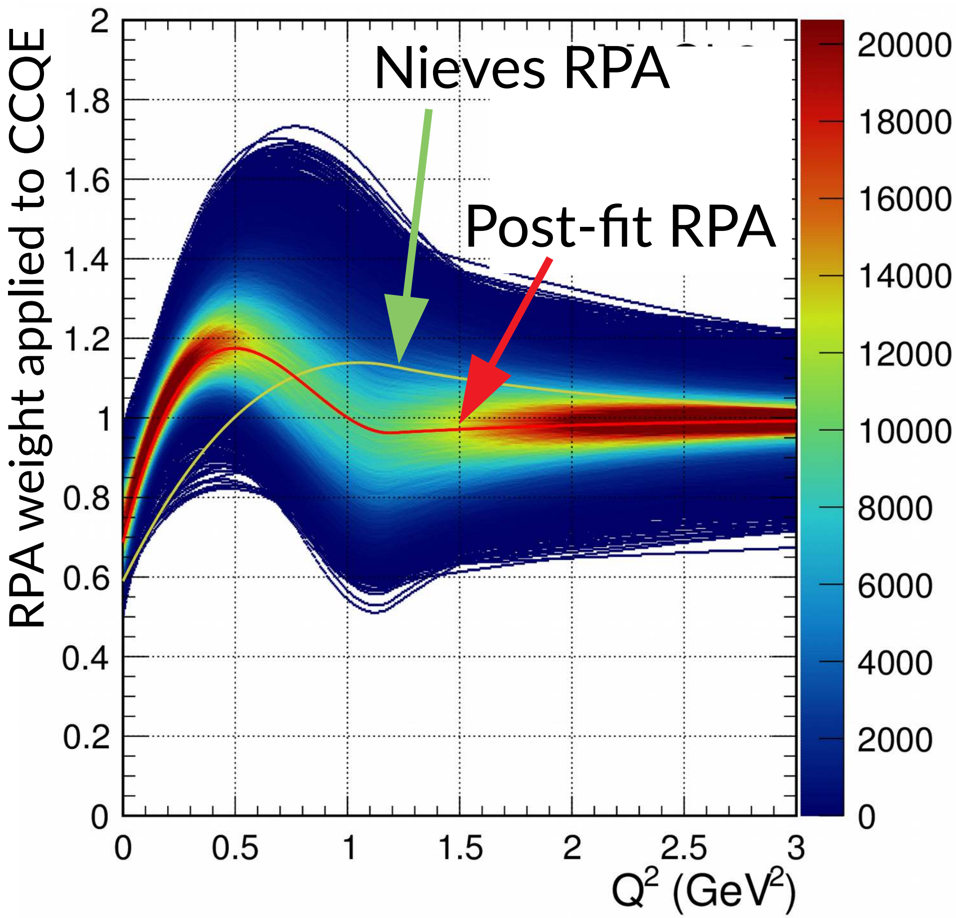


- Indicates the nominal nuclear model is insufficient
  - An effective T2K-only model in the making?
  - Evaluate by extensive comparisons/fits to external data

The near detector fit

- Clear improvement on the pre-fit
- RPA shape post-fit doesn't resemble Nieves RPA



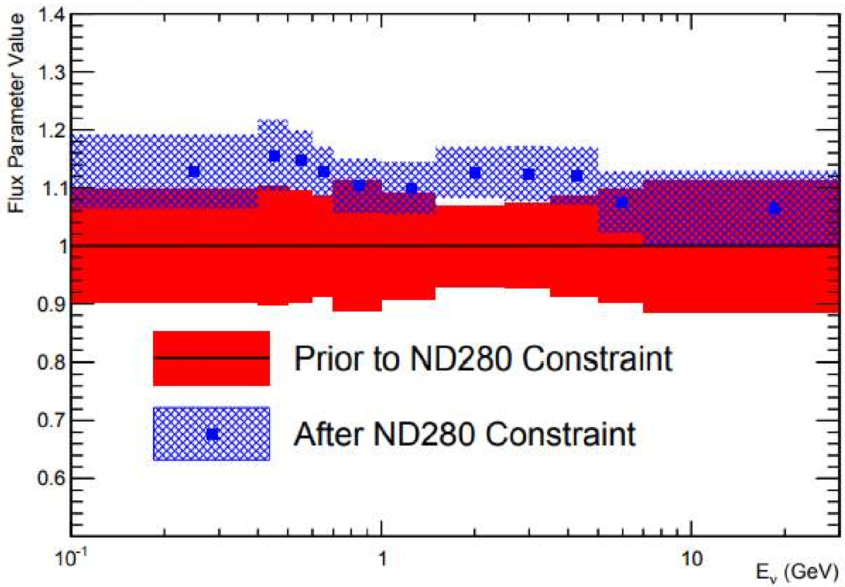


- P-value ~ 47%
  - CCOther selections only bad news: 0-1% good
  - CCOther has negligible impact on SK selections

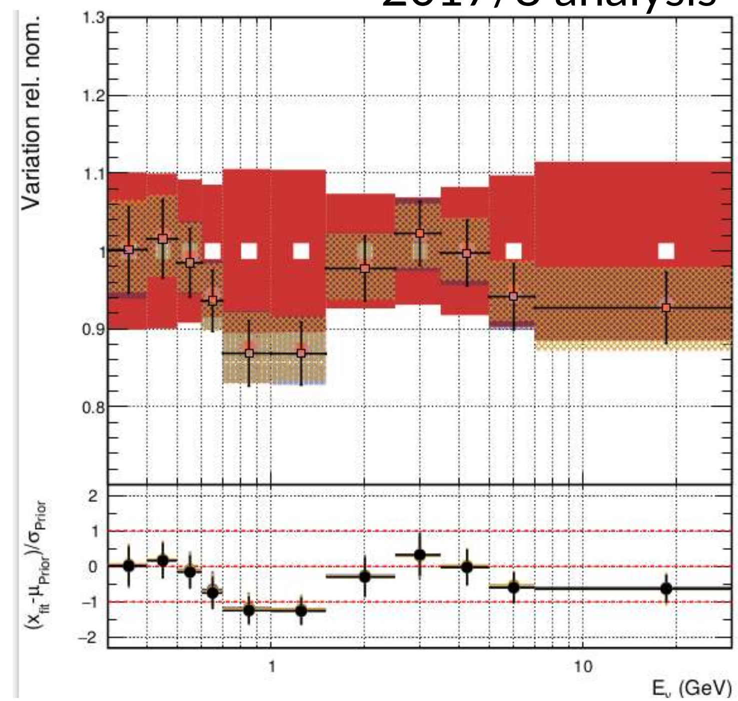
The near detector fit

- The 2015 flux increase is now absorbed in the RPA parameters

2015/6 analysis



2017/8 analysis

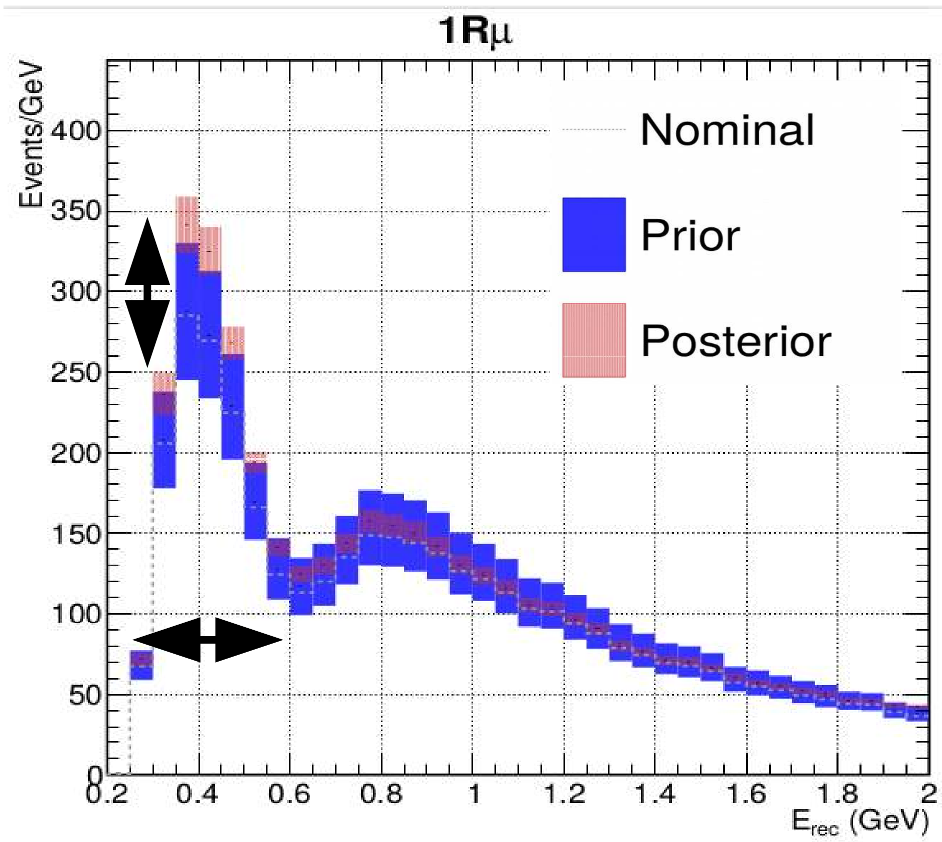


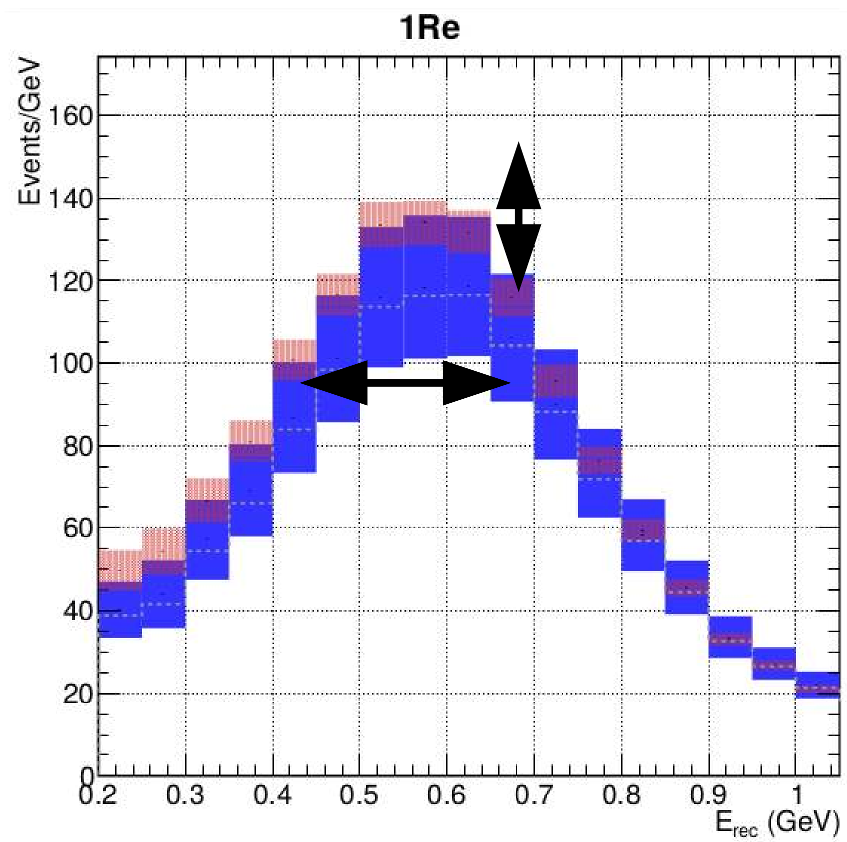
- Replacing one bad egg with another?
- ND280 data wants a Q^2 (q_0, q_3?) dependent correction
- Evaluate the post-fit interaction model against neutrino scattering data to gauge how T2K-specific the tune is: complicated due to flux parameters
- Might rethink BeRPA for next year: try Rik Gran RPA and develop more

https://arxiv.org/abs/1705.02932

The far detector prediction

- Look at the prediction for the SK E_ν^{rec} spectrum with and without the fit (posterior vs prior)





- Clear reduction in uncertainty on event spectrum
- Changes the prediction in the oscillation dip, need to evaluate what effect this may have

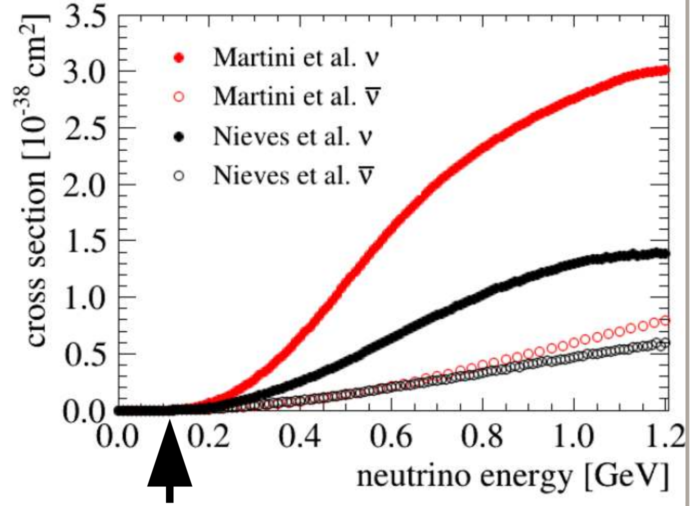
Mock data studies

- Evaluates impact of interaction model choice on extracted oscillation parameters
- Reweight simulation to some model not covered in the simulation, and set these template to be the “mock data”
- Fit the simulation at ND280 and SK with the normal model to the “mock data”
- Check to see if the extracted oscillation parameters differ to when using the Asimov data
- If large difference, devise method for oscillation parameter inflation
- Is not equivalent to re-running simulation, but approximate and much less time-consuming
- Full list in backups

- *Details of the T2K oscillation analysis*, D. Sgalaberna, Thur. 2.30pm

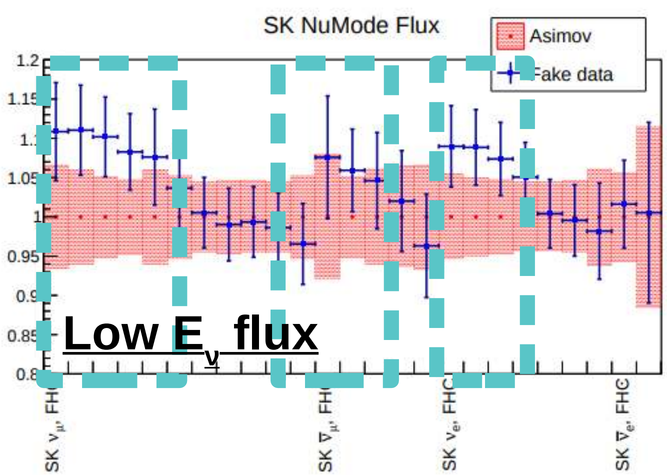
Example mock data

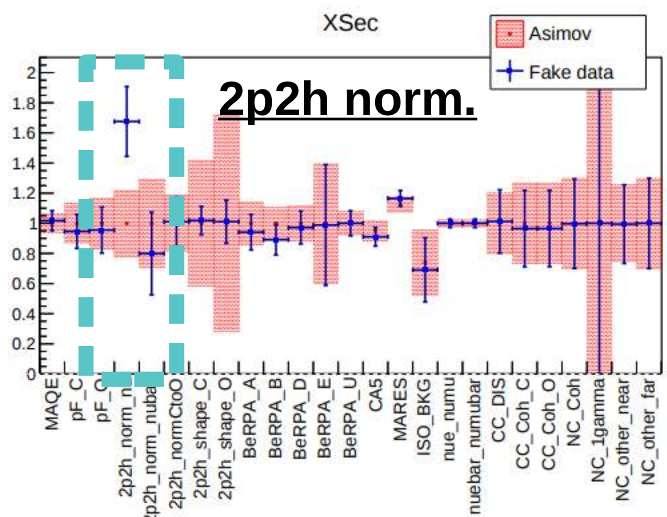
- Martini 2p2h vs Nieves 2p2h



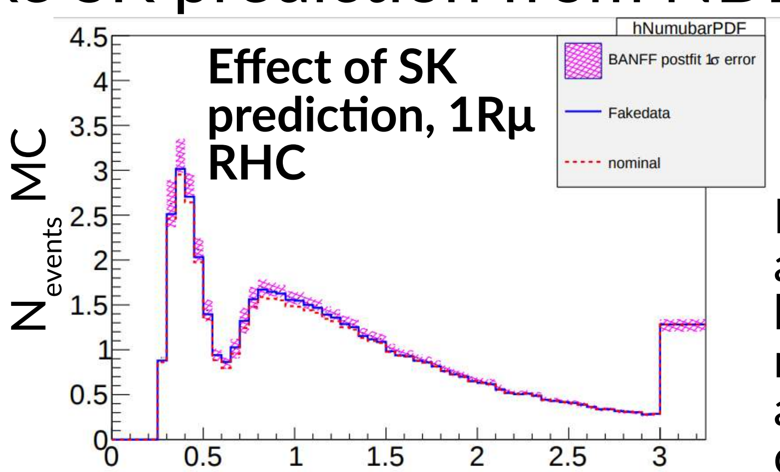
Total cross-section of 2p2h, Martini and Nieves

- Near detector fit shows change in parameters: model absorbing difference

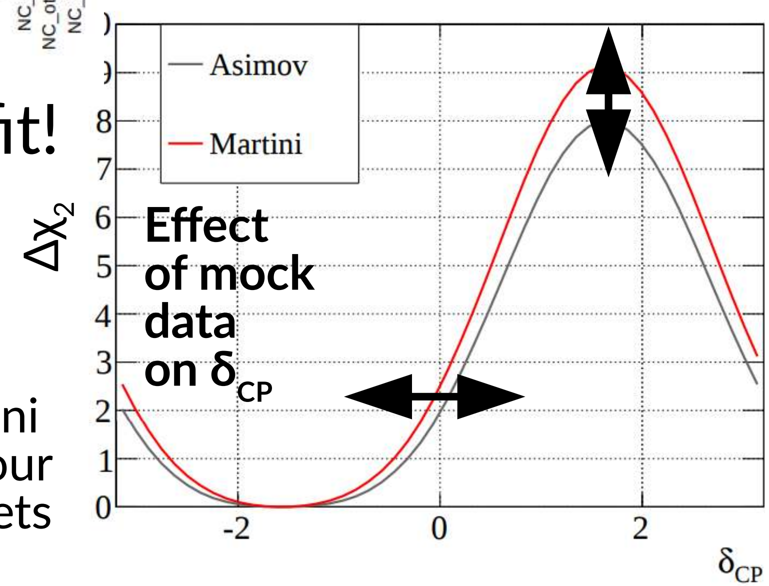




- Make SK prediction from ND280 and fit!



If 2p2h is actually Martini but we have our model, T2K gets a stronger constraint on δ_{CP}



What's ~~needed~~ desired

- Addressed with new NEUT 5.4.0 production:
  - Include LFG for more interaction modes than CCQE
  - Including Nieves 1p1h and 2p2h with hadron tensor
  - M. Kabirnezhad single pion model Phys. Rev. D 97, 013002
- More work on multi-generator OA:
  - Recent GENIE and NuWro versions with ReWeight
  - GiBUU as a comparison (no systematics)
- Compare the post ND280 fit model to other experiments' equivalent (e.g. MINERvA and NOvA tune)
- Smaller issue: CC DIS model is poor at ND280

Conclusions

- T2K's recent interaction parameterisation is the most sophisticated to date
- Capturing more nuclear physics than previous analyses, including shape freedom in 2p2h and RPA
  - 2p2h shape and BeRPA pushed beyond 1σ
- The inputs to the ND280 and SK fit are carefully checked against external data
- Current model is satisfactory in muon variables with T2K flux and target, but lots of room for improvement
- Devised methods for evaluating interaction model dependence on oscillation analysis results: upcoming long paper

- <u>Crucial to nurture collaboration between interaction theorists, generators, and experiments!</u>

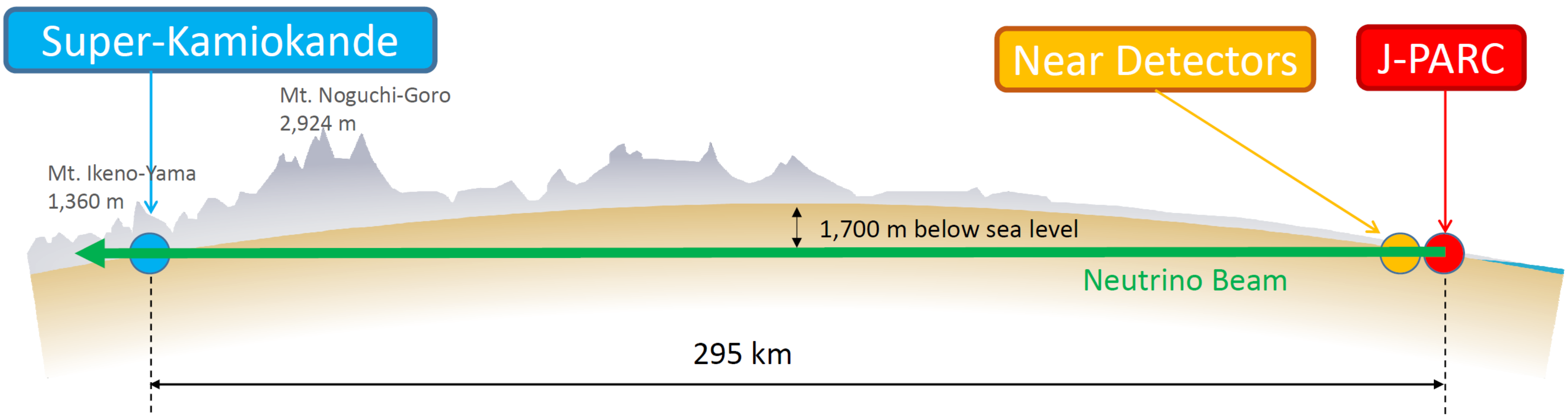
Thank you!

T2K Breakthrough Prize Party
January 28th, 2016 at Kuji Sunpia Hitachi

Backups

The T2K experiment

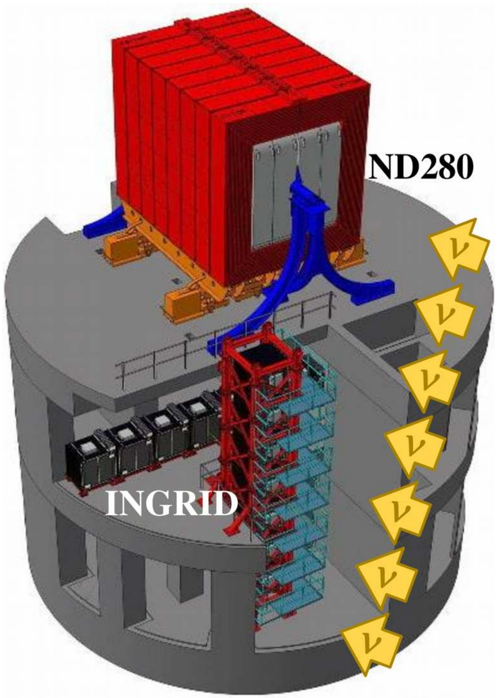
- Long baseline neutrino oscillation experiment



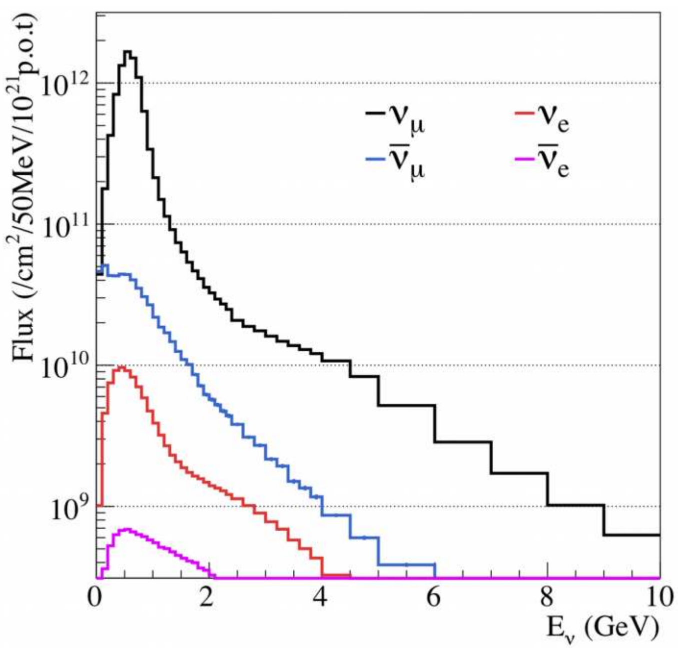
- Near detectors – 280 m from target
  - Constrains flux before oscillation and interaction physics
  - Measurements of neutrino cross sections for the community
  - Exotic measurements, e.g. steriles and HNL
- Far detector – 295 km from target
  - Apply model constraints from near detector and external data, add-on SK detector model and oscillations
  - Cross sections and exotics are also measured

The near detectors

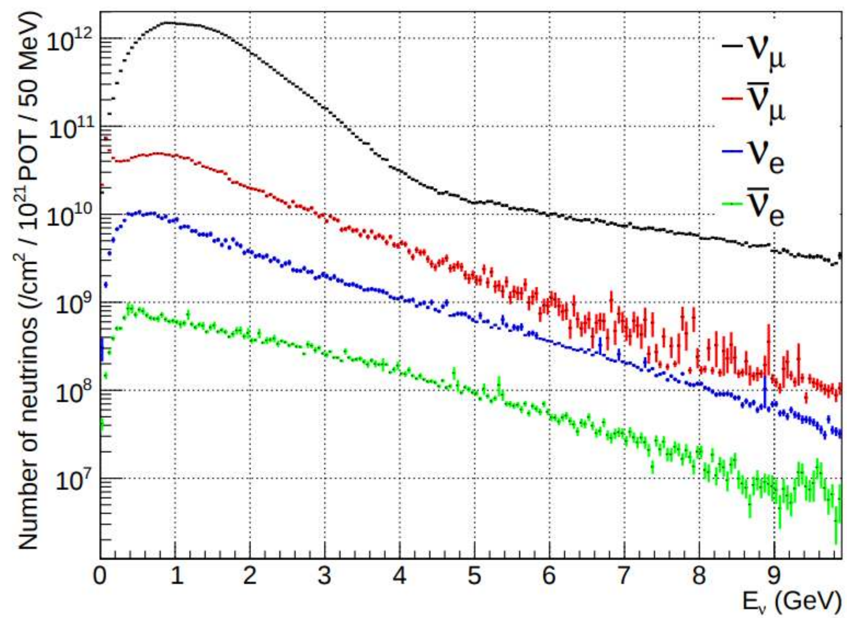
- Fluxes: ν_μ and anti-ν_μ dominated with different E_ν
  - ND280: 2.5° off-axis, 0.6 GeV narrow band: constrain cross section
  - INGRID: On-axis, 1.3 GeV wide band: constrain neutrino beam



ND280 flux (off-axis)



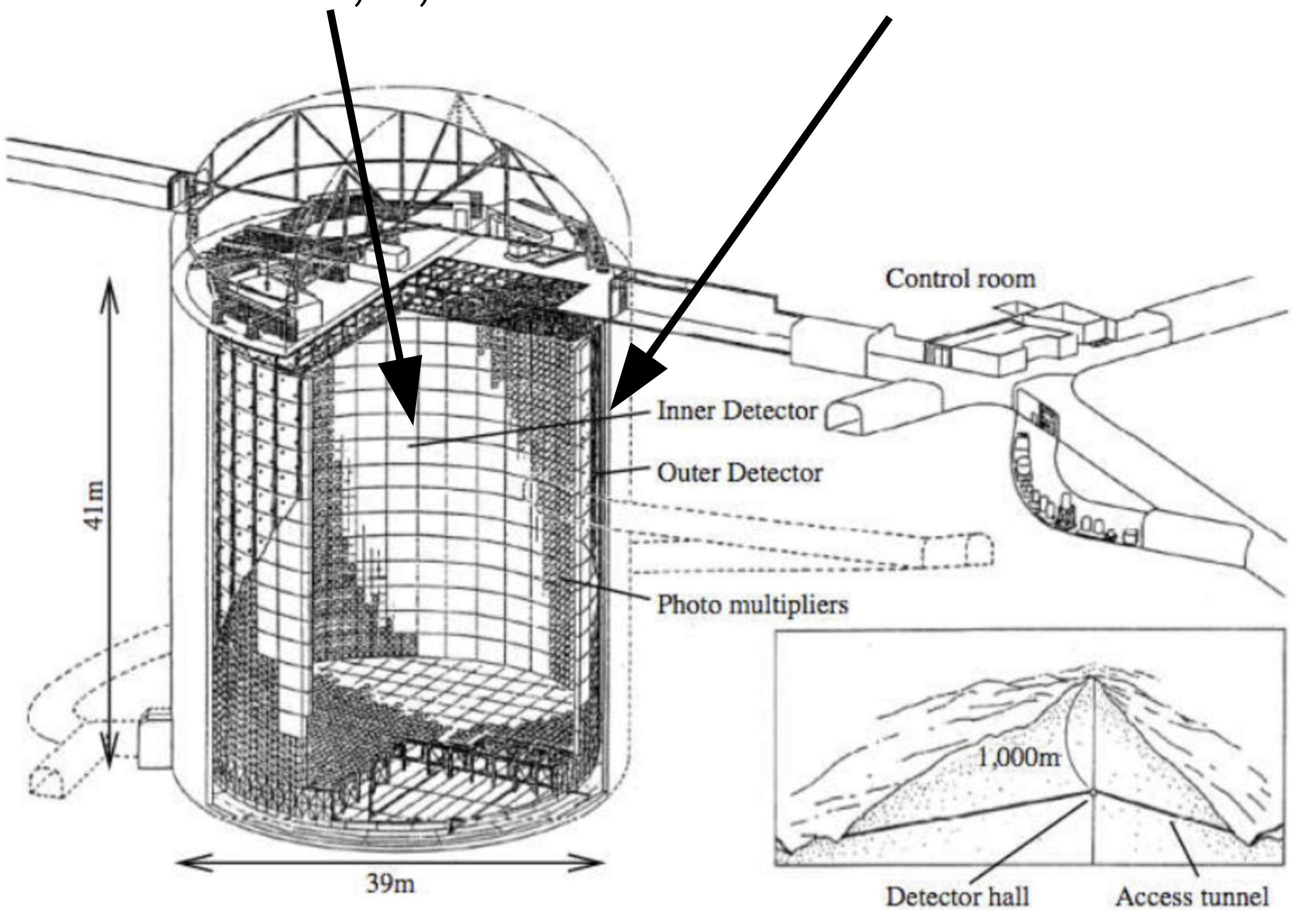
INGRID flux (on-axis)



- Multiple targets in INGRID and ND280: C_8H_8, H_2O, Ar, Pb, Fe
- More detectors being rolled in!

Super-Kamiokande far detector

- 50kt water Cherenkov detector, 2.7 km water equivalent overburden
- Running since 1996, with last upgrade SK-IV in 2008
  - 2.5° off-axis with similar flux to ND280
- 11,146 20” PMTs in ID, 1,885 8” PMTs in OD – 40% PMT coverage



- Excellent μ/e separation: <1% mis-assign e as μ and vice versa

ND280 sub-detectors

TPC: Time Projection Chamber:

Gaseous Ar

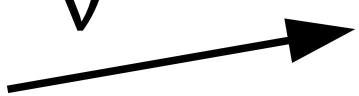
ECAL: Electromagnetic calorimeter

C_8H_8, Pb

FGD: Fine Grained Detector:

C_8H_8, H_2O

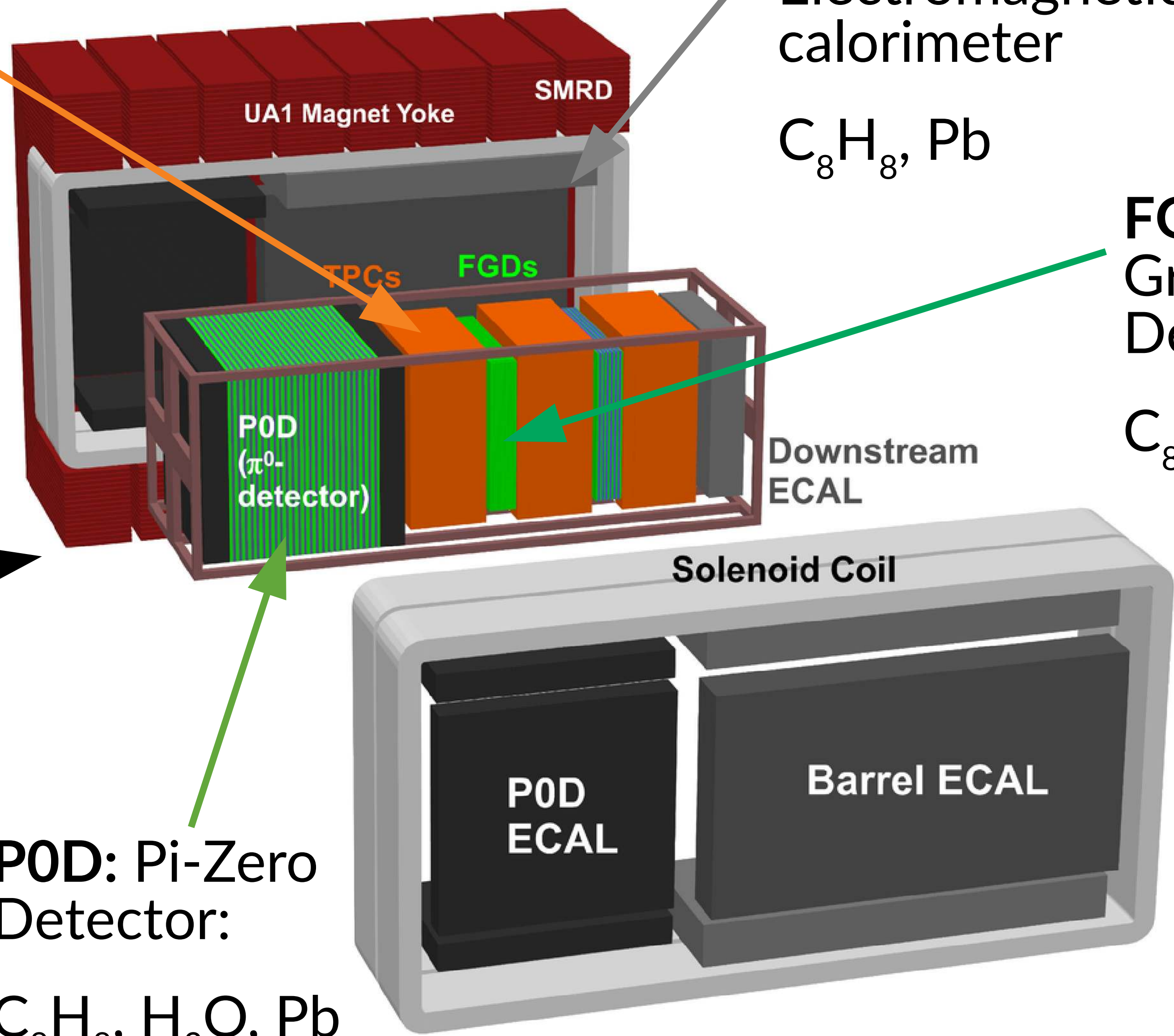
ν



ν

ν

ν

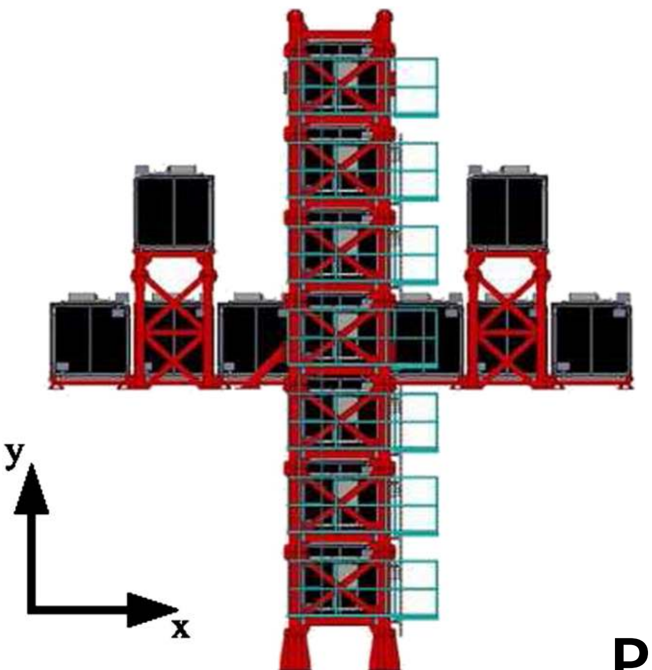


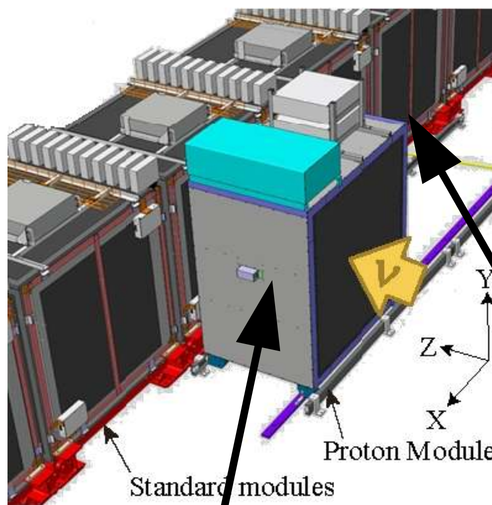
P0D: Pi-Zero Detector:

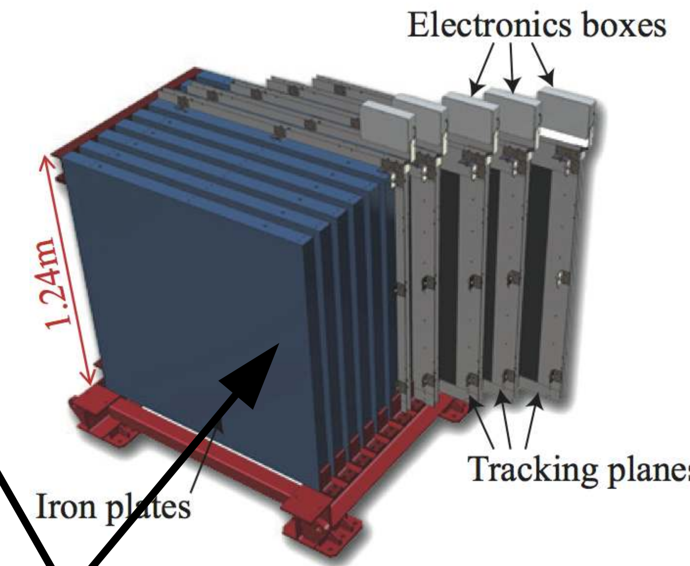
C_8H_8, H_2O, Pb

The INGRID detector

- Organised in cross pattern for beam direction measurements
- Proton module for dedicated cross section modules
  - No iron plates: fully plastic scintillator





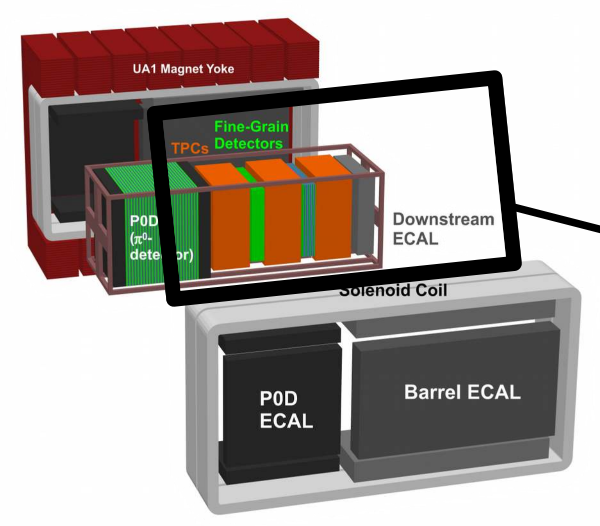


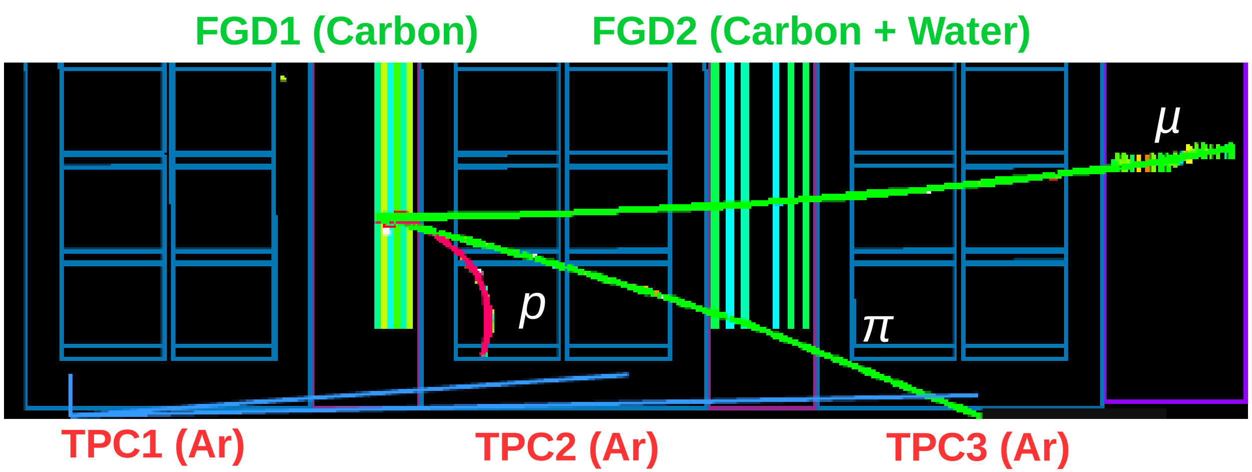
Proton Module:
Fully C_8H_8

INGRID:
C_8H_8, Fe plates

ND280 selections

- Use FGD1 and FGD2 in ND280 as targets: CH and H_2O



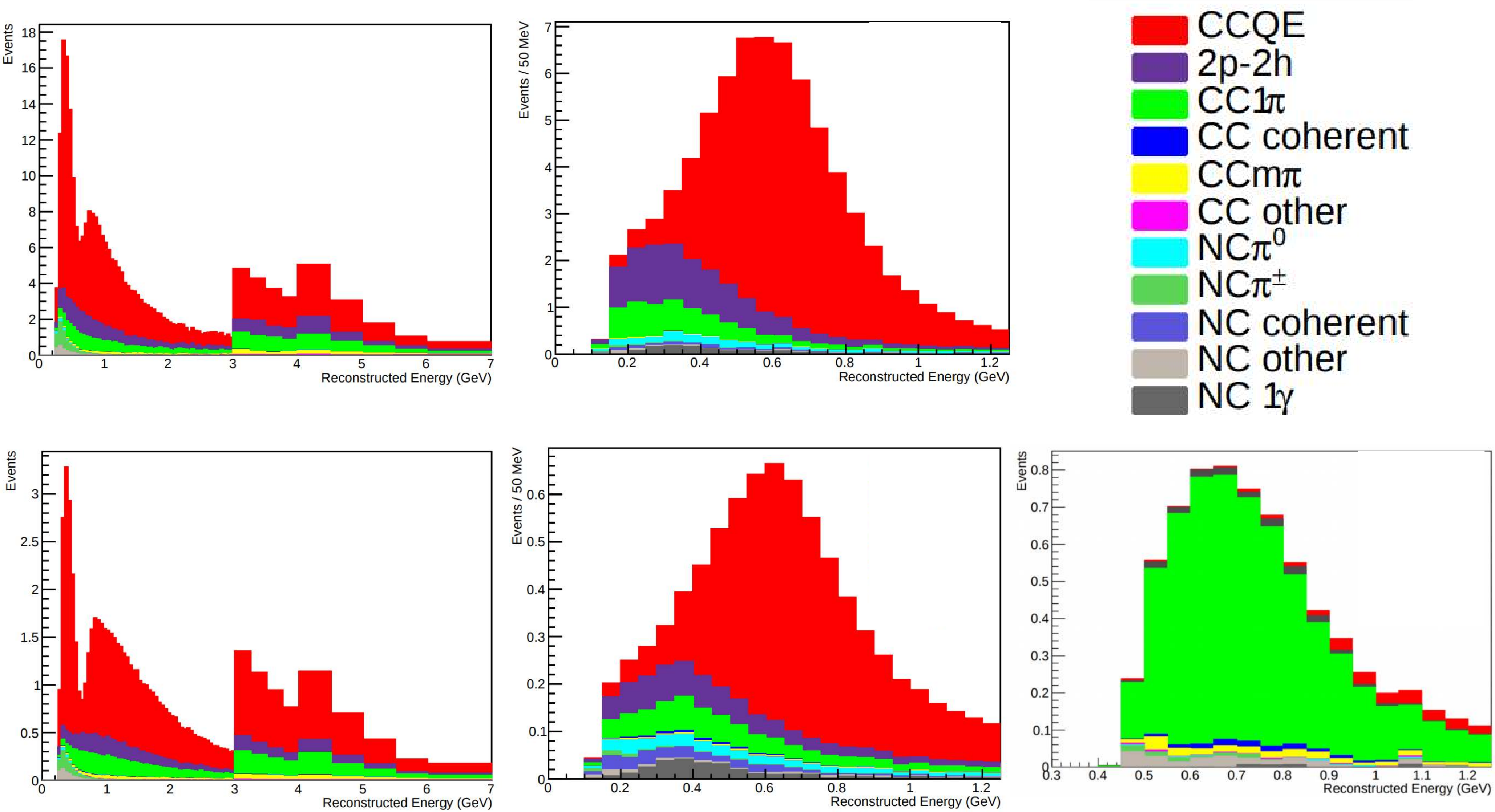


- 14 topological event selections (data events per FGD up to 2015)†:
  - **<u>ν</u>**: CC0π (17000), CC1π (4500), CCOther (4000)
  - **<u>Anti-ν</u>**: CC1Trk (2700), CCNTrk (800), CC1Trk ν bkg (900), CCNTrk ν bkg (1000)
- Selections are developed by the cross-section groups
- Constrains oscillation signal interaction (CC0π) and backgrounds (1π, CCOther or NTracks, neutrino in anti-neutrino)

†Doubling in 2018 analyses

SK selection breakdown

- Event selection with Asimov A oscillation after ND280 fit constraints



T2K's 2018 parameterisation

- RFG with dipole form factor
  - Can also use Spectral Function (Benhar et al.) but was chosen against after MiniBooNE+MINERvA fit
- 2p2h from Valencia group
- 1p1h RPA from Valencia, applied to our RFG model
  - Technically incorrect, but Nieves estimated it's roughly alright
- Rein-Sehgal with 18 resonances, interference, and a non-resonant background P11(1450). Matter effects included, form factor choice Graczyk & Sobczyk
- Coherent Rein-Sehgal with p_pi normalisations to roughly match Berger-Sehgal and MINERvA data
- Multi-pi as transition from Rein-Sehgal to DIS in 1.3 < W < 2.0 GeV. Custom routine for the extrapolation
- DIS modelling through PYTHIA 5.9
- Pion final state interactions Salcedo Oset
- Nucleon final state interactions Bertini cascade

T2K's 2018 parameterisation

<u>Underlined means prior used</u>

- MAQE, MAQEH, pF C, pF O
- 2p2h norm nu, anti-nu, <u>C to O</u> – uncorrelated
- 2p2h shape C, 2p2h shape O – correlated 30%
- <u>BeRPA A, B, D, E</u> – uncorrelated
- <u>MARES, C5A, I1/2 bkg</u> – correlated by fit
- <u>CC coh norm C, CC coh norm O</u> – correlated fully
- <u>CC other shape</u>, weight = value*0.4/Enu
- <u>NC coh norm, NC 1gamma norm, NC oth norm</u>
- <u>CC nue/numu ratio, CC nuebar/numubar ratio</u>
- <u>Pion FSI parameters: abs., inel. Lo, inel. hi, charge ex lo, elastic (no charge ex hi)</u>

Mock data studies

- Many alternative models tested:
- ND280 data-driven
  - All differences in all selections due to 1p1h, 2p2h Delta-like or 2p2h non Delta-like
- MINERvA data-driven
  - Apply Gaussian weights in q_0, q_3 to 1p1h or 2p2h events to match the MINERvA data
- ND280 data driven pion momentum in true p_π
- Z-expansion CCQE alternative form factors
- Nieves 1p1h, CCQE Spectral Function
- Martini 2p2h model
- M. Kabirnezhad single pion production model
- Binding energy variations migrating events