Constraining systematics at T2K with near-detector data

Using the 2016/7 analysis as an example

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On behalf of ND280 fitting group

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MELIORA

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T2K

Outline

- Need for near detector fits
- The T2K oscillation analysis chain
- Selections at ND280
- Systematics at ND280
- Making it all fit
- Looking forwards

Estimating SK event rates

- Number of predicted events at SK has dependence on flux and cross-section model

$$N_{SK} \sim \boxed{\Phi_{SK}(E_\nu)\,\sigma(E_\nu)}\,\epsilon_{SK} P(\nu_\alpha \rightarrow \nu_\beta)$$

- Large systematics from flux and cross-sections: can be improved by fitting near-detector data

FHC ν_μ

	Pre-BANFF			Post-BANFF		
Group	Mean	1σ	%	Mean	1σ	%
Flux+Xsec constrained	250.34	35.35	14.12	266.68	8.60	3.22
All	250.95	35.71	14.23	267.78	11.79	4.40

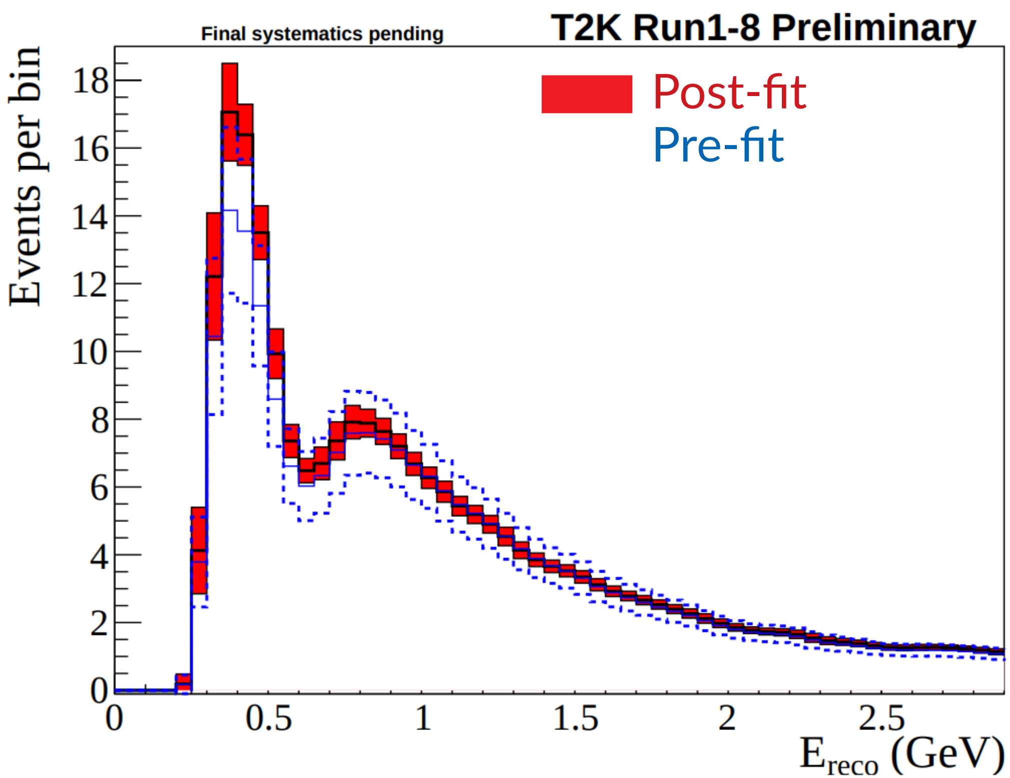
FHC ν_e

	Pre-BANFF			Post-BANFF		
Group	Mean	1σ	%	Mean	1σ	%
Flux+Xsec constrained	62.09	7.18	11.56	63.97	1.74	2.72
All	62.18	7.31	11.76	64.17	2.41	3.76

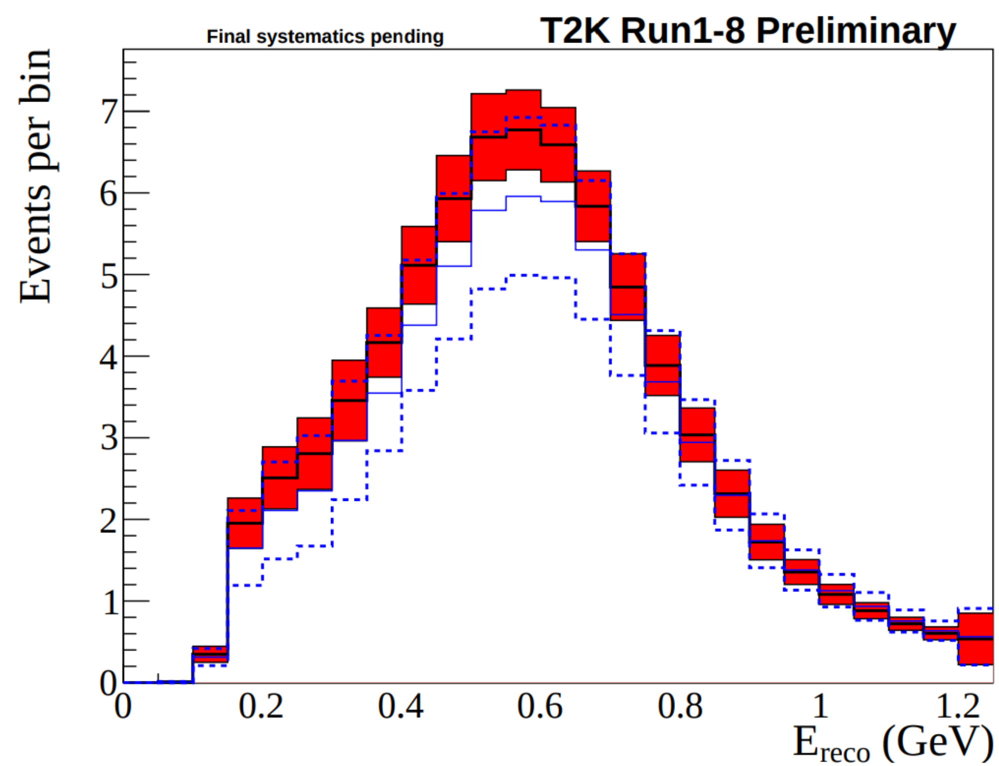
- Changes central value and uncertainty in SK event spectra

Estimating SK event rates

- Allows for shape and normalisation changes of un-oscillated spectrum



FHC ν_μ

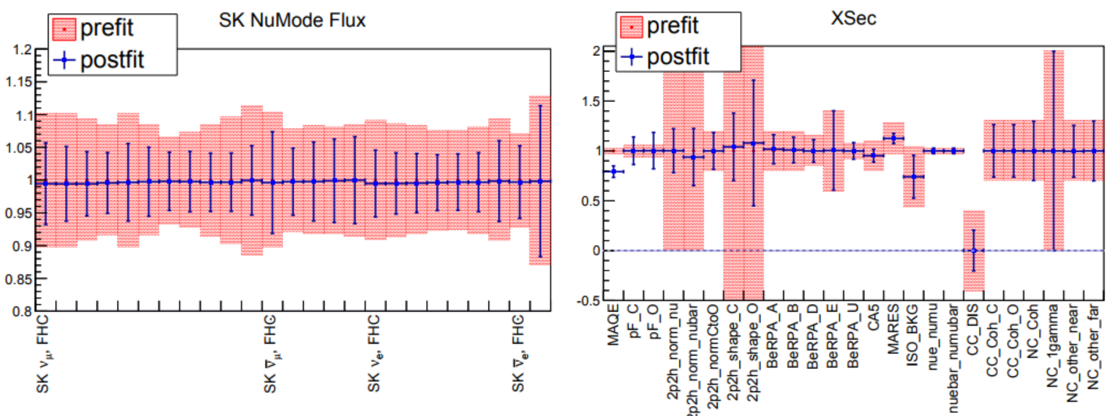


FHC ν_e

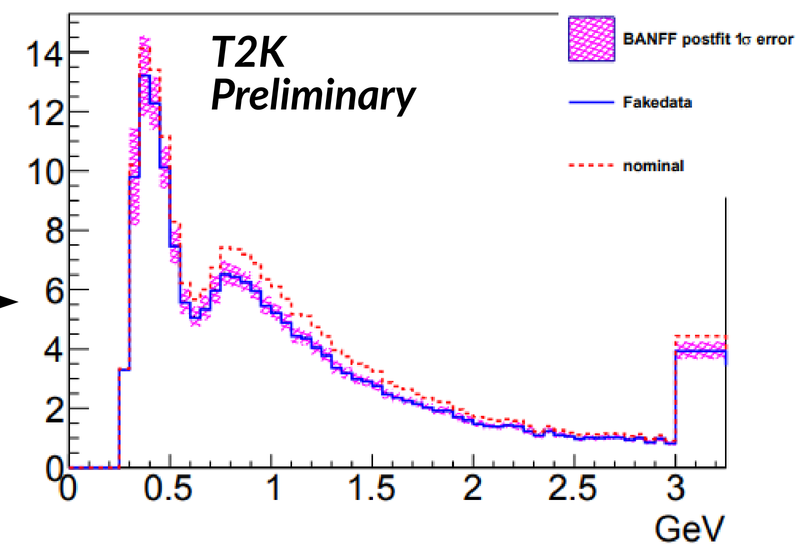
Estimating SK event rates

- Fit may mimic oscillation parameters, needs thorough attention
- Use alternate model as "data" and fit with our model: "fake-data" studies
  - If we have model A but model B is actually nature, how do we bias our oscillation parameters?

<u>Fit z-expansion fake-data at ND280</u>

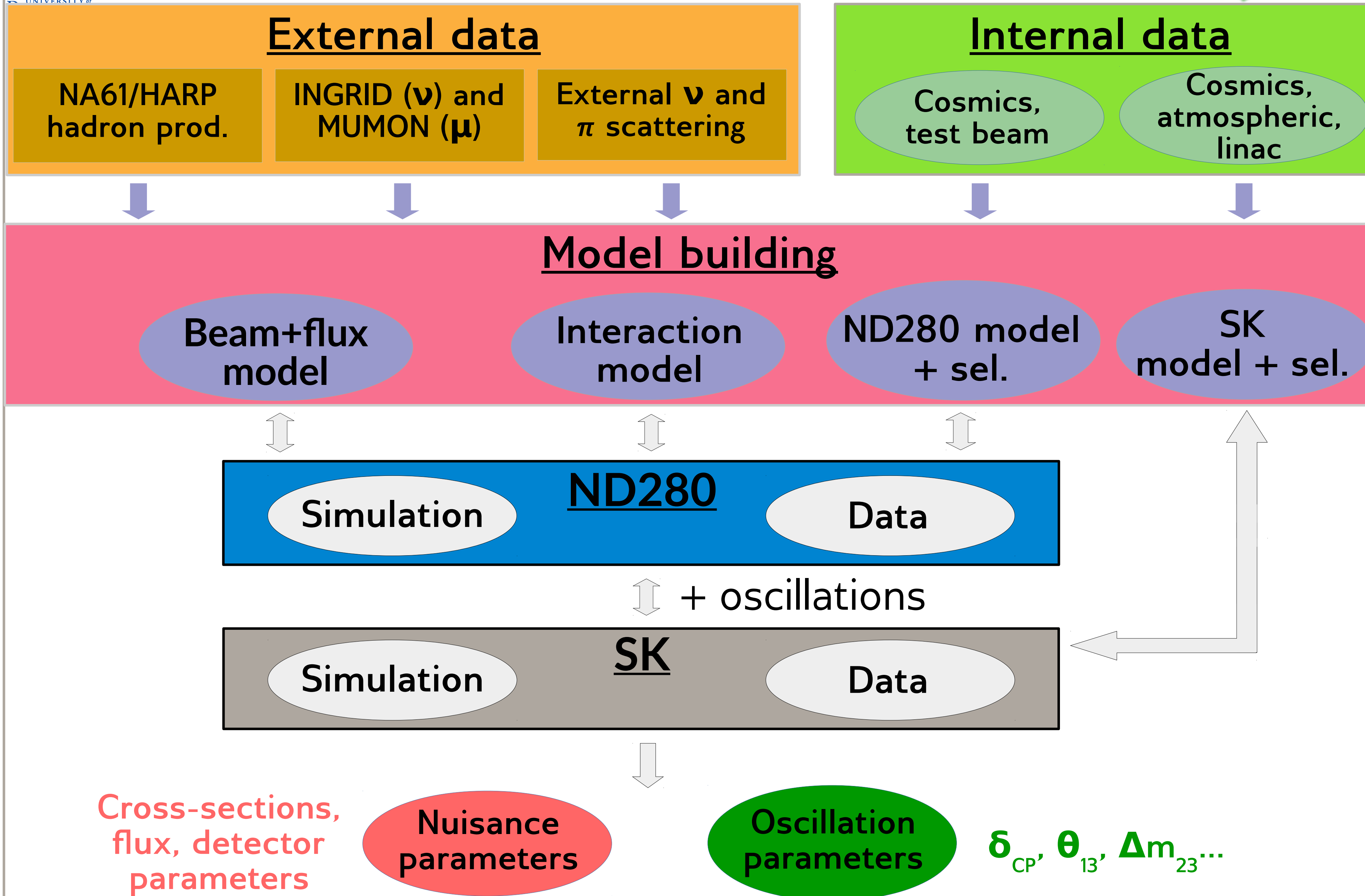


<u>Propagate to SK prediction</u>



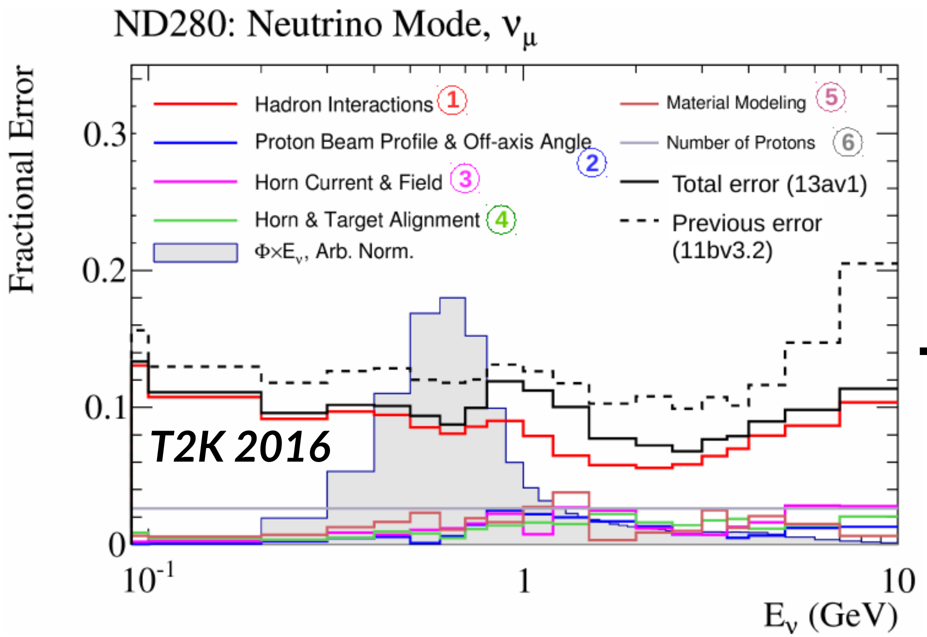
- Create "fake-data" at both ND280 and SK, propagate through oscillation analysis

T2K oscillation chain

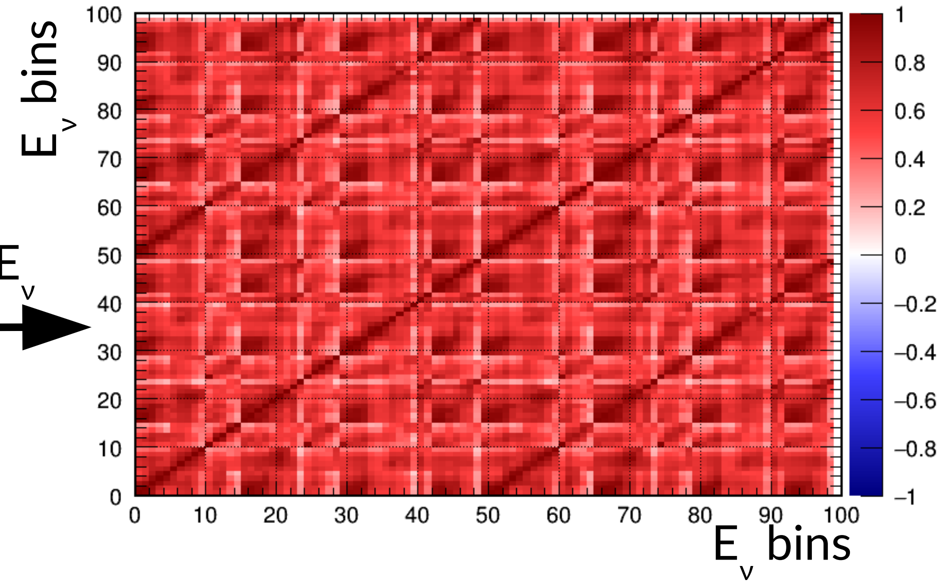


Flux systematics

- Bin up changes to underlying beam simulation
  - Highly correlated normalisation parameters in E_ν



Bin in E_ν



- Binning in E_ν for FHC(PF)/RHC(NF) ND280 and SK reflect flux shape

ν_μ PF/$\bar{\nu}_\mu$ NF: 0.0, 0.4, 0.5, 0.6, 0.7, 1.0, 1.5, 2.5, 3.5, 5.0, 7.0, 30.0

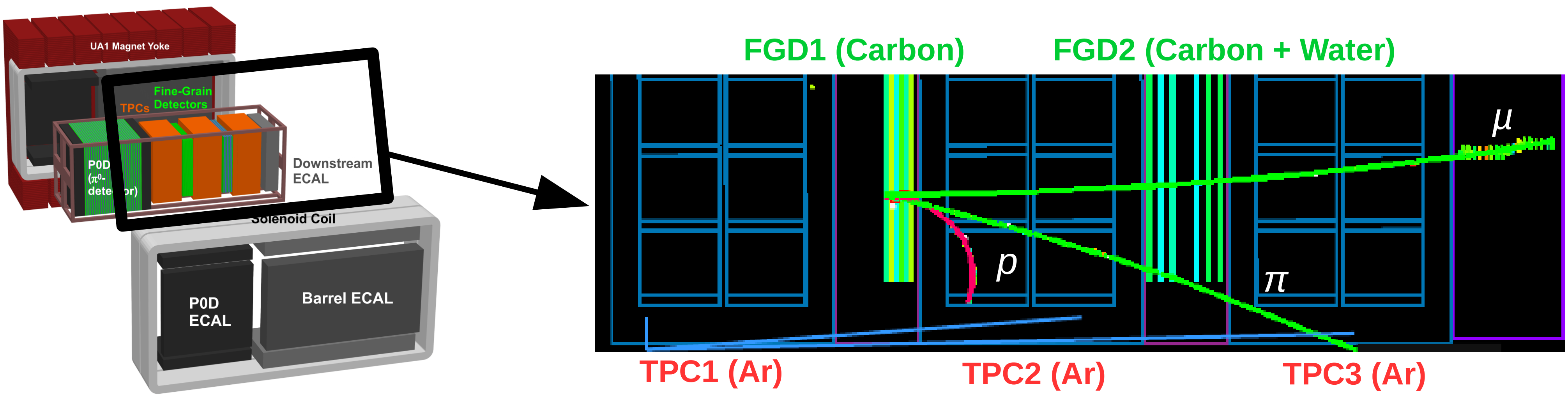
$\bar{\nu}_\mu$ PF/ν_μ NF: 0.0, 0.7, 1.0, 1.5, 2.5, 30.0

ν_e PF/$\bar{\nu}_e$ NF: 0.0, 0.5, 0.7, 0.8, 1.5, 2.5, 4.0, 30.0

$\bar{\nu}_e$ PF/ν_e NF: 0.0, 2.5, 30.0

ND280 selections

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



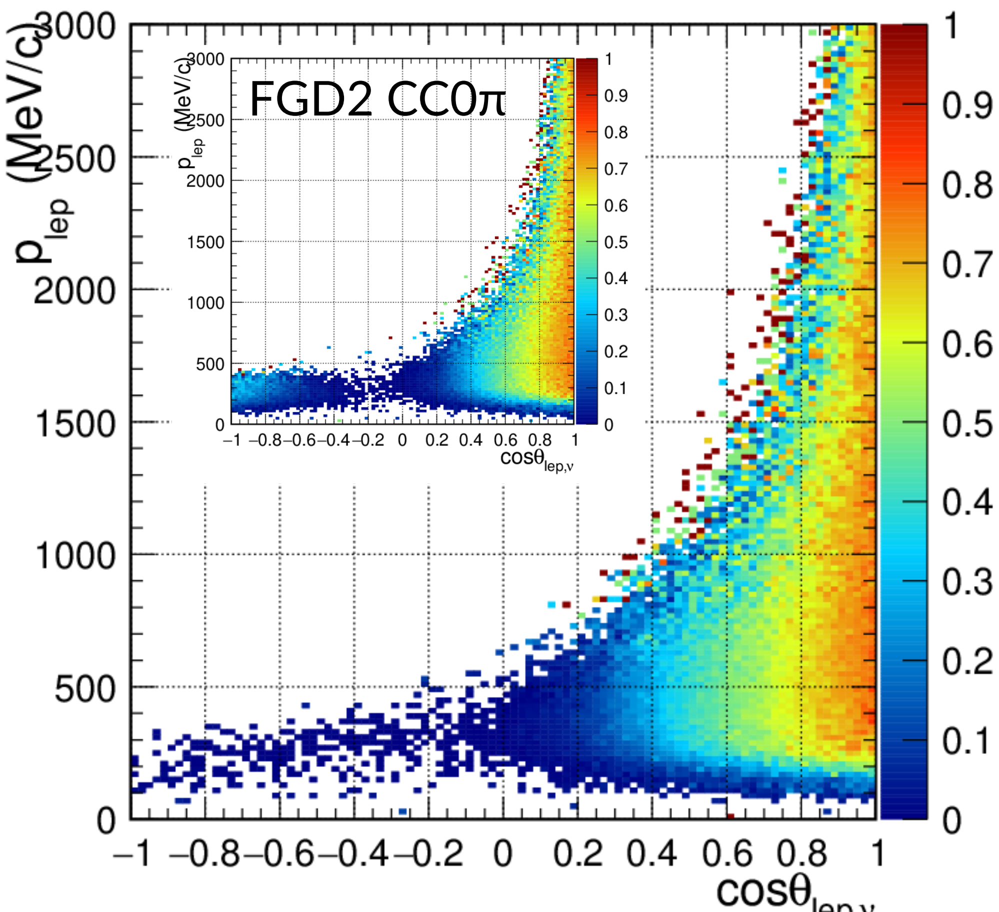
- 14 topological event selections (data per FGD up to 2015)†:
  - <u>ν</u>: CC0π (17000), CC1π (4500), CCOther (4000)
  - <u>**Anti-ν**</u>: CC1Trk (2700), CCNTrk (800), CC1Trk ν bkg (900), CCNTrk ν bkg (1000)
- Selections are developed by the cross-section groups
- Constrains oscillation signal interaction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

†Doubling in 2018/9 analyses

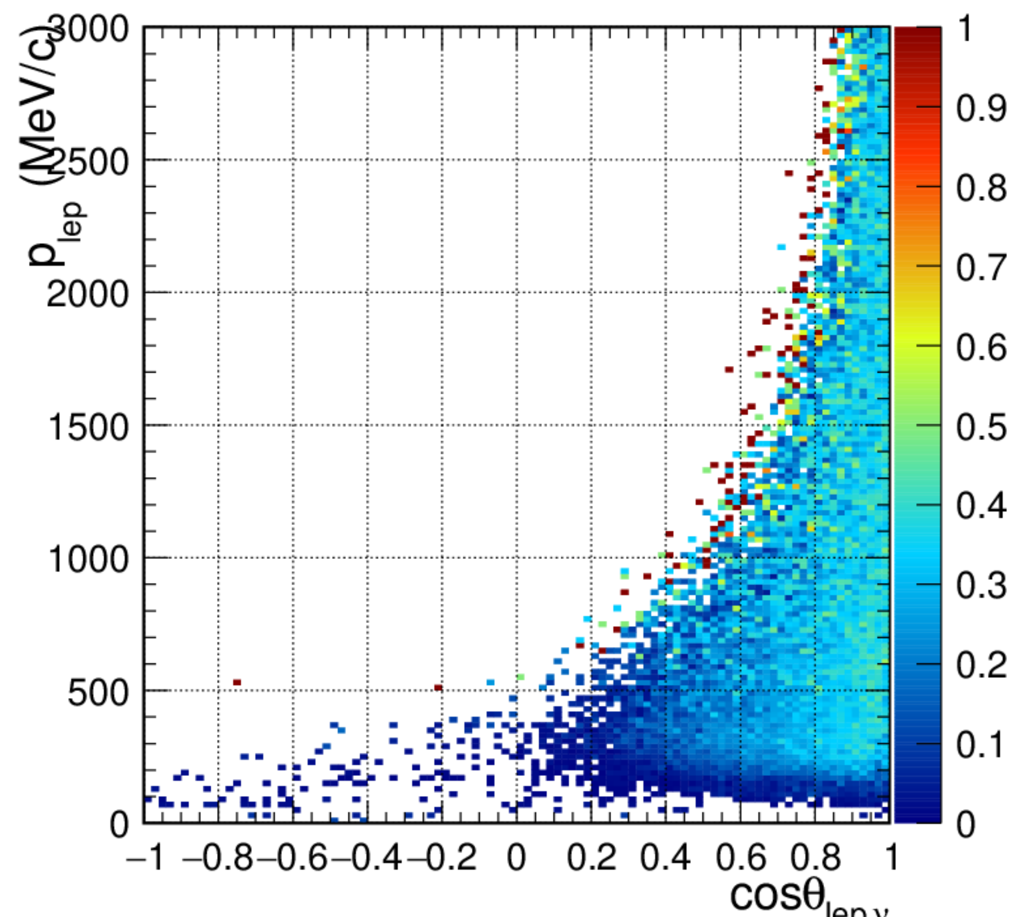
Efficiencies/acceptances

- Forward-going acceptance high for 0π: 0.6-0.9
  - Structure in $\cos\theta_\mu$ from forward-focussed geometry
- Flat-ish in momentum above 250 MeV

FGD1 CC0π

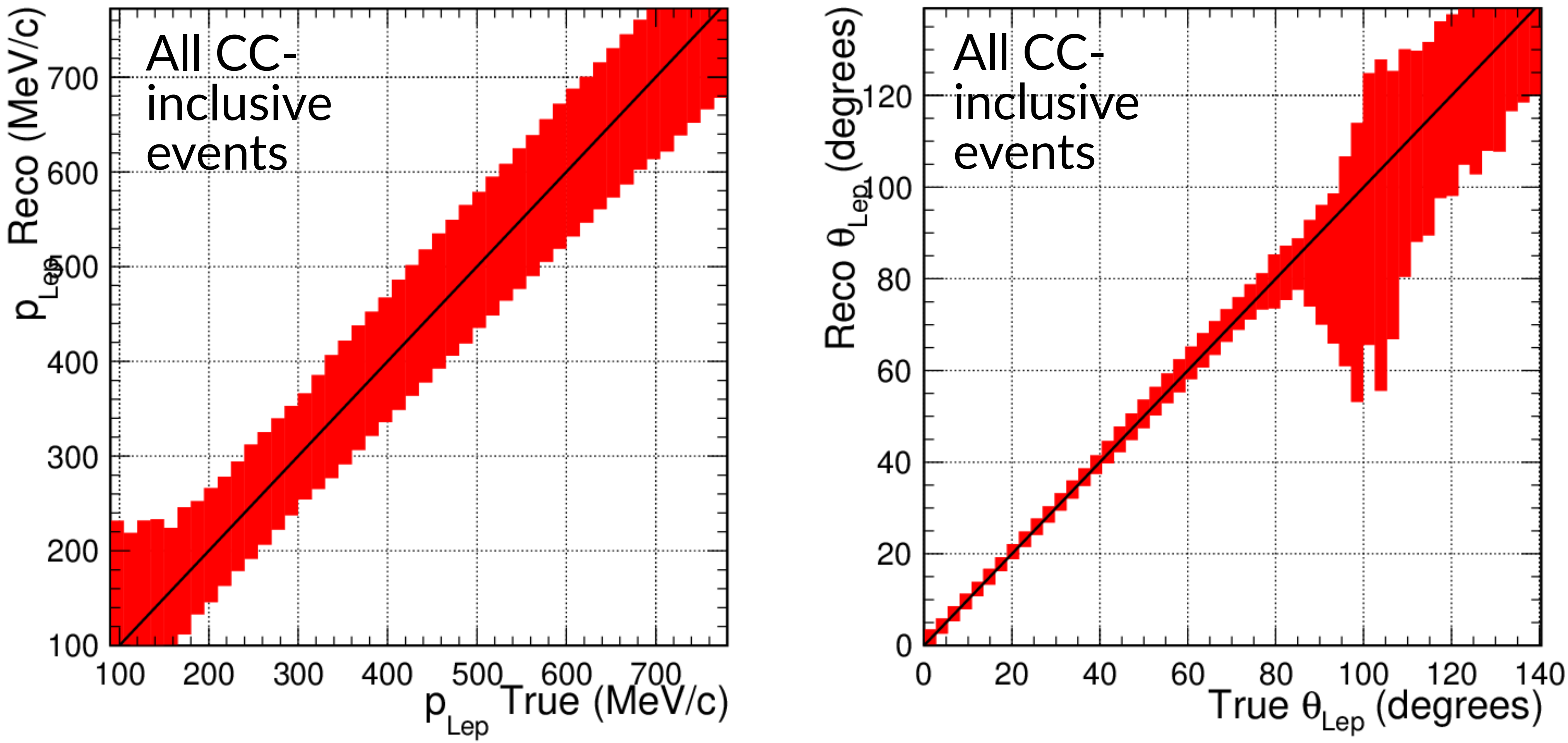


FGD1 CC1π



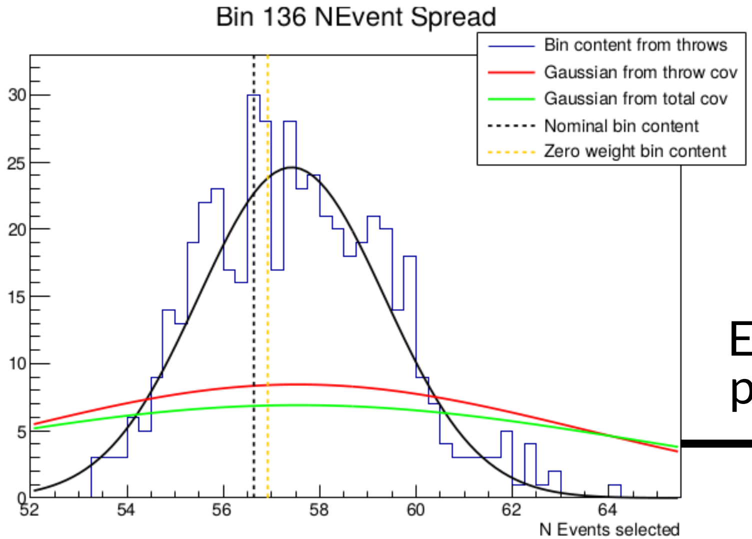
Resolutions

- Unbiased above p_μ = 150 MeV/c, uncertainty between 50-100 MeV/c
- Above θ_μ=70º angles is uncertain and biased



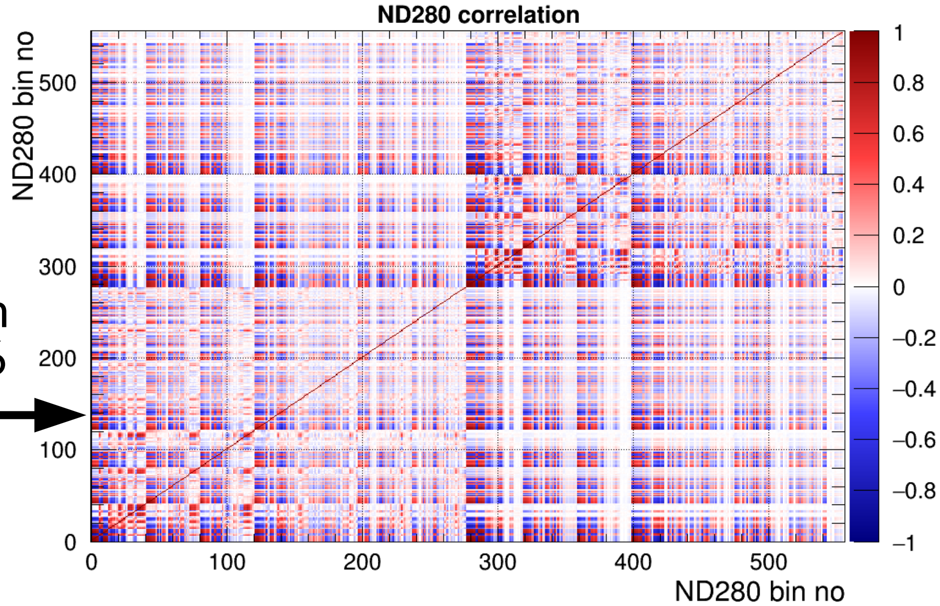
ND280 systematics

- Fit and systematics binned as normalisations in (p_μ, $\cos\theta_\mu$)
  - Less sensitive to nuclear effects or FSI (vs e.g. T_π or q_0q_3) but very good reconstruction in ND280
- Vary underlying ND280 detector parameters, e.g. TPC PID, B-field distortions, momentum scales (backups)



FGD1 CC1Trk selection, $p_\mu = 0 - 400$ MeV/c, $\cos\theta_\mu = 0.97 - 0.98$

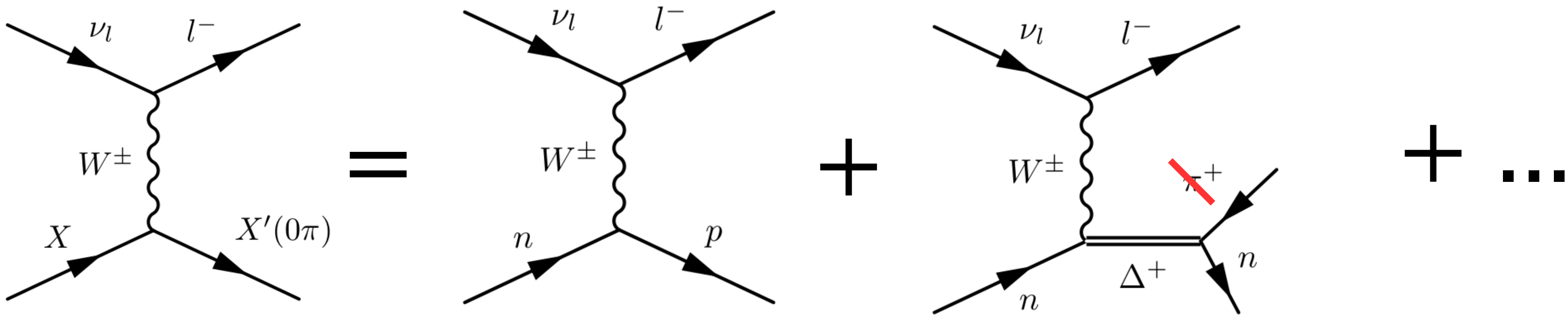
Enters as norm parameter 136



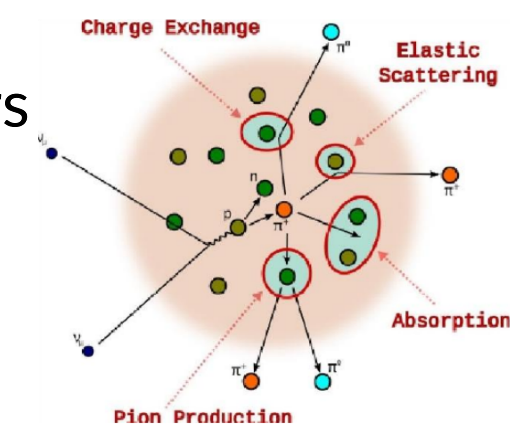
- Desire to move to direct event-by-event detector re-weighting
  - Significant computational overhead

Cross-section systematics

- Rapidly developing field: update model every analysis
- 2016/7 analysis: 31 systematics in NEUT MC
- 12 CCQE(-like) systematics:
  - M_A^{QE} is the only nucleon parameter
  - 2p2h shape and normalisation parameters, RPA shape and normalisation



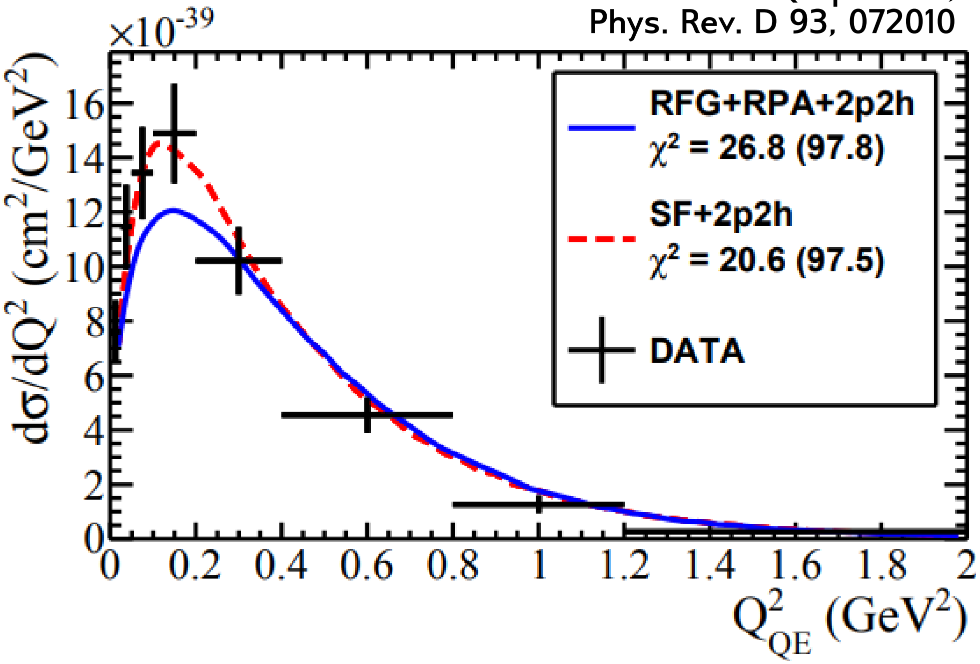
- 3 CC1π on nucleon + 3 CC1π coherent parameters
- ν_μ/ν_e normalisation for neutrino and anti-neutrino
- 6 pion final state interaction parameters
- CC DIS, CCOther, NCOther, NC1γ



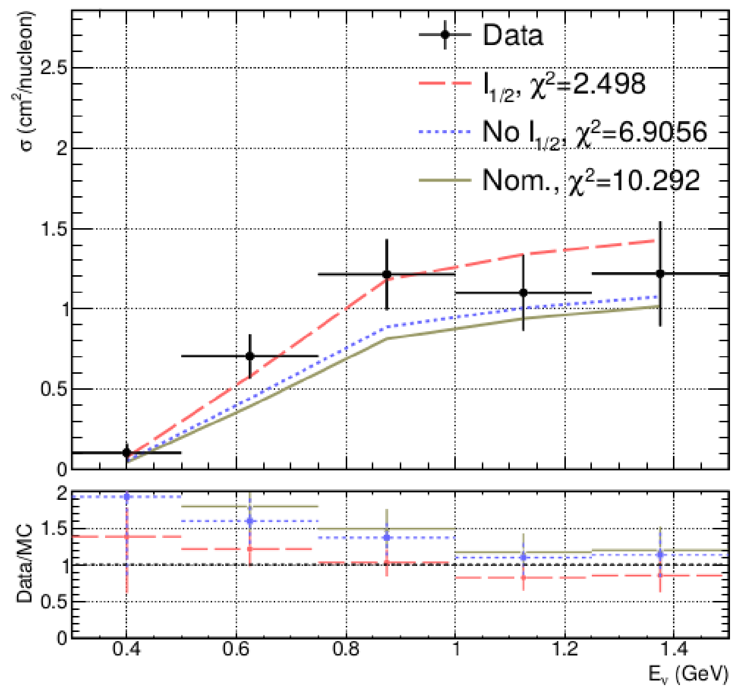
Setting up the fit

- Use constraints for all the flux and ND280 systematics
  - Developed by the beam group and selections group
- Cross-section parameters get external constraints from the Neutrino Interaction Working Group (NIWG)
  - Using external data with NUISANCE

MINERvA CCQE post-fit,
Phys. Rev. D 93, 072010



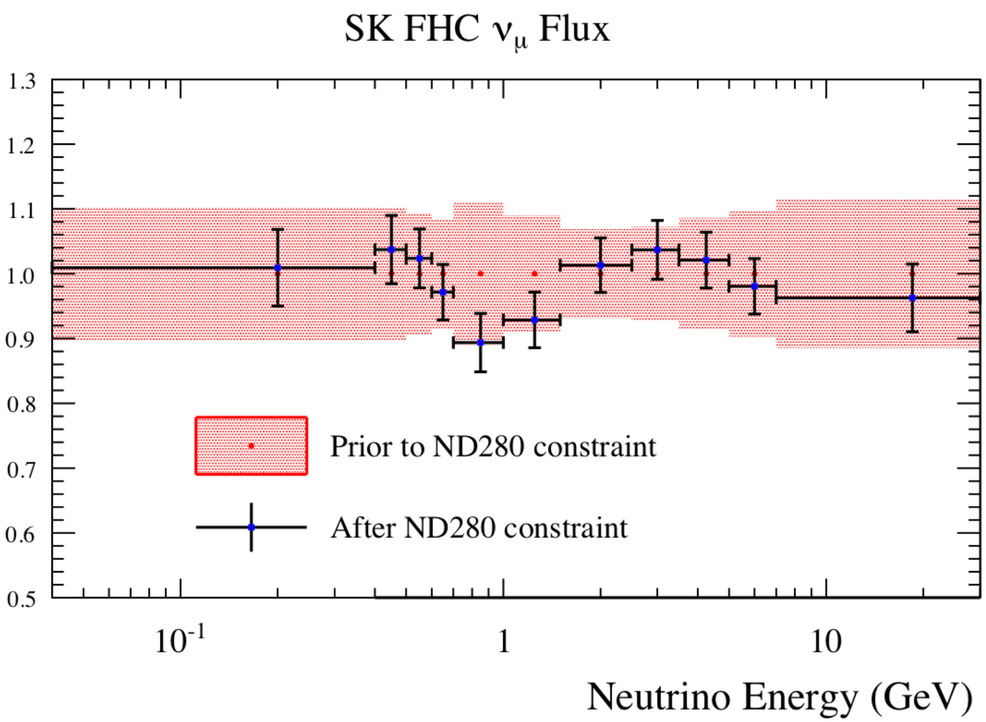
ANL CC1pi+1n post-fit, internal T2K 2017

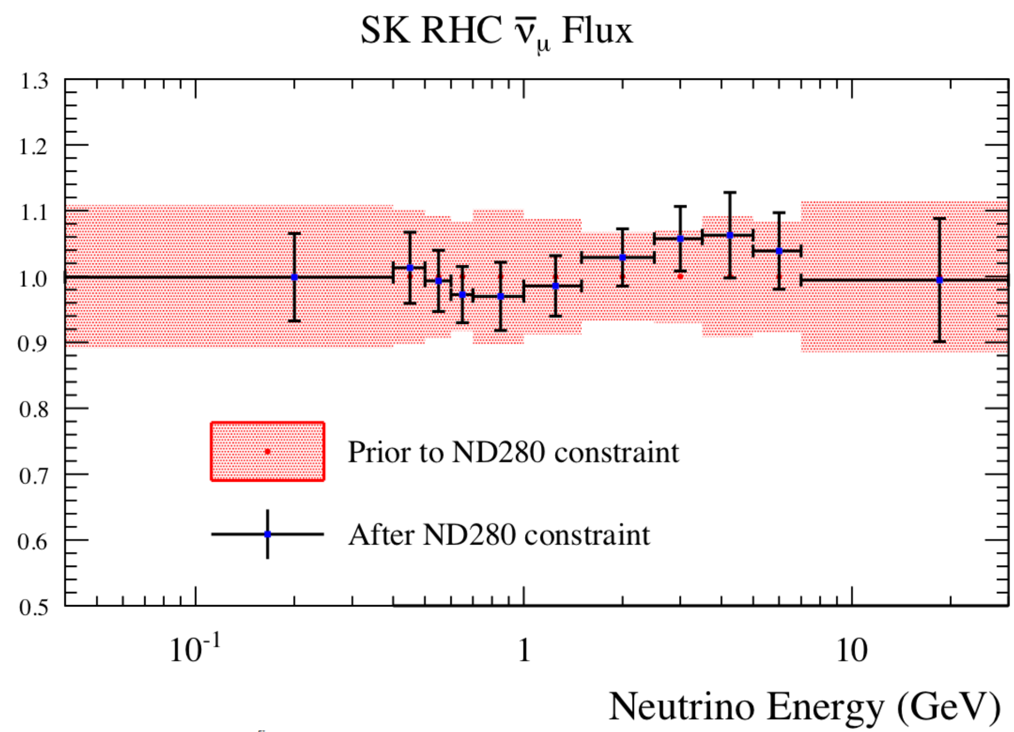


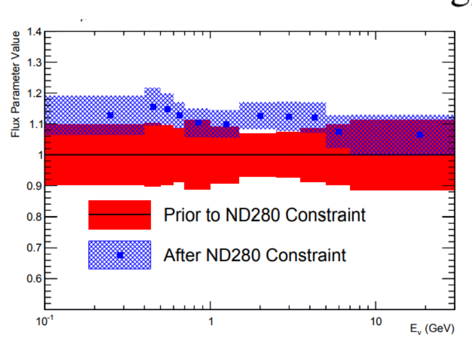
  - Phenomenological arguments, e.g. ν_μ/ν_e and C to O scaling

2017 ND280 data fits, flux

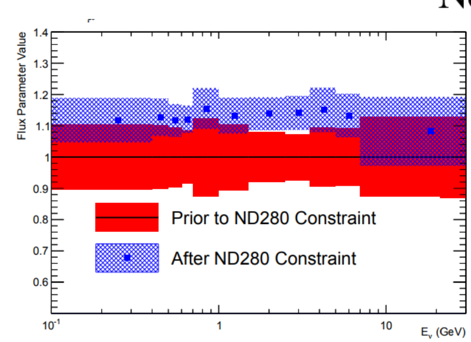
- 1.0 is nominal un-tuned model: variation is relative uncertainty
- 2014/5 analysis' +10% flux pulls are gone (see bottom inset)
  - Encouraging? Moving towards "realistic" model?





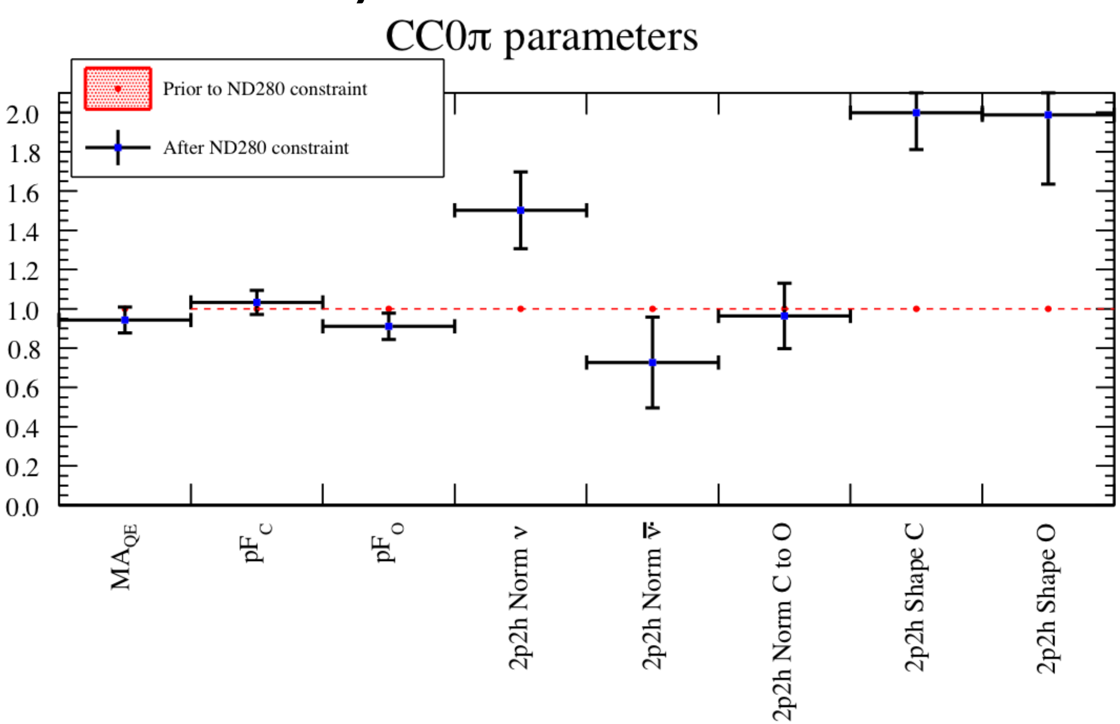


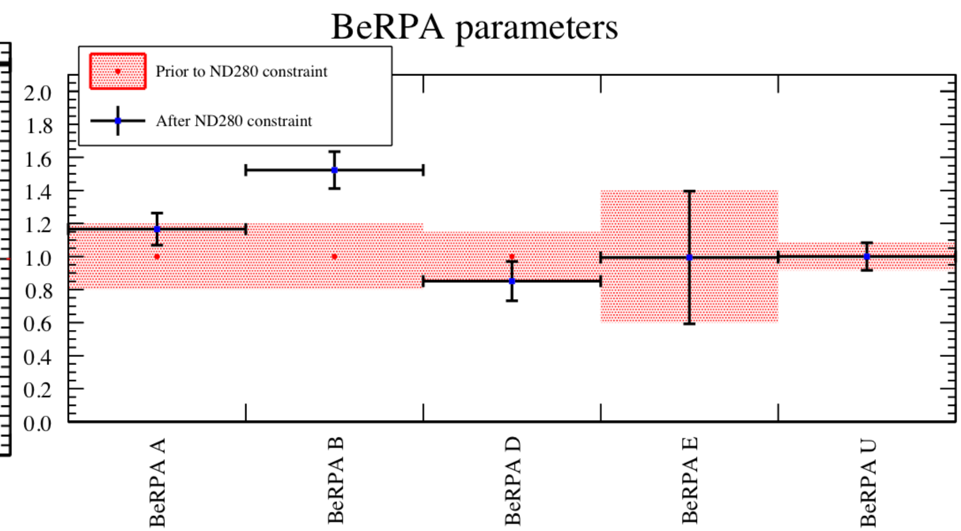
2014/5 analysis



2017 ND280 data fits, xsec

- M_A^{QE} still inflated (1.13 GeV), even without prior and nuclear eff.
- Large excursions from priors for RPA, 2p2h shape pushed to boundary

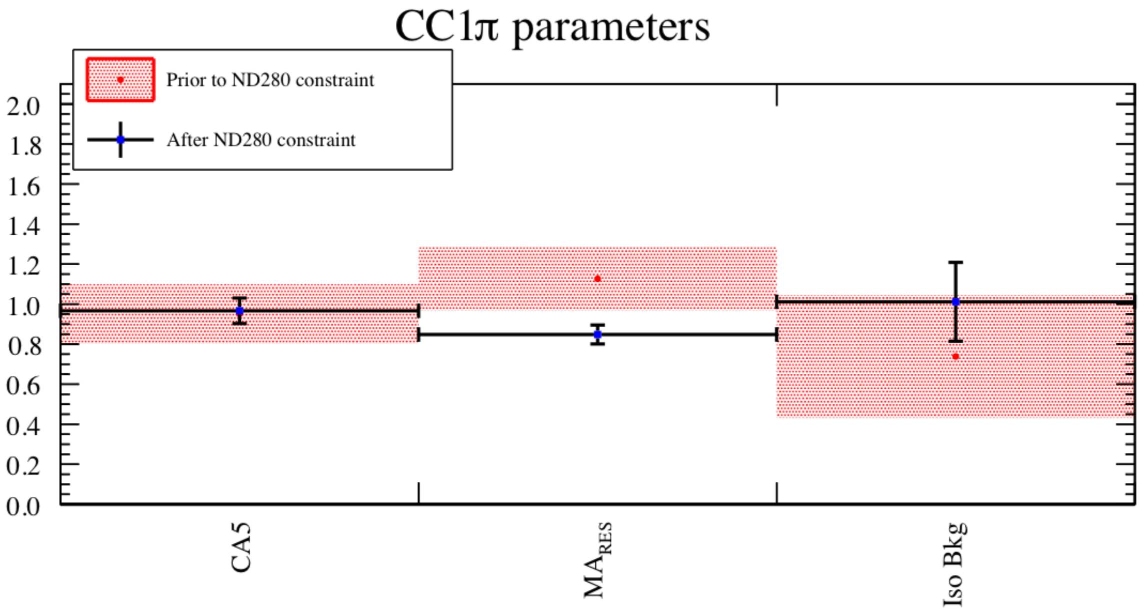


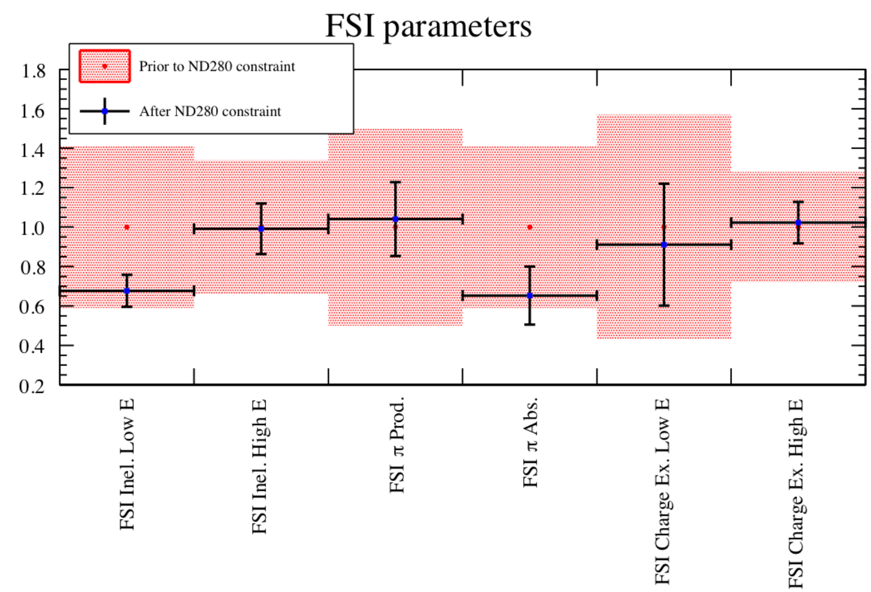


- 2p2h norm for neutrino and anti-neutrino is different (1.5 vs 0.7)
- 1σ uncertainties are exceeded for RPA
- Our 2p2h shape parameter pushed to pionless-Delta-like

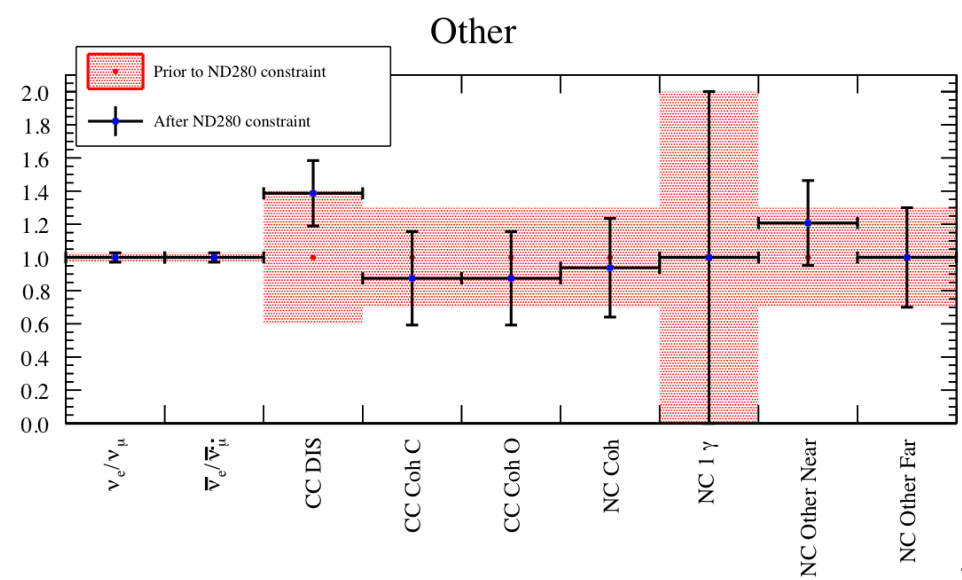
2017 ND280 data fits, xsec

- Non CC0π parameters better behaved





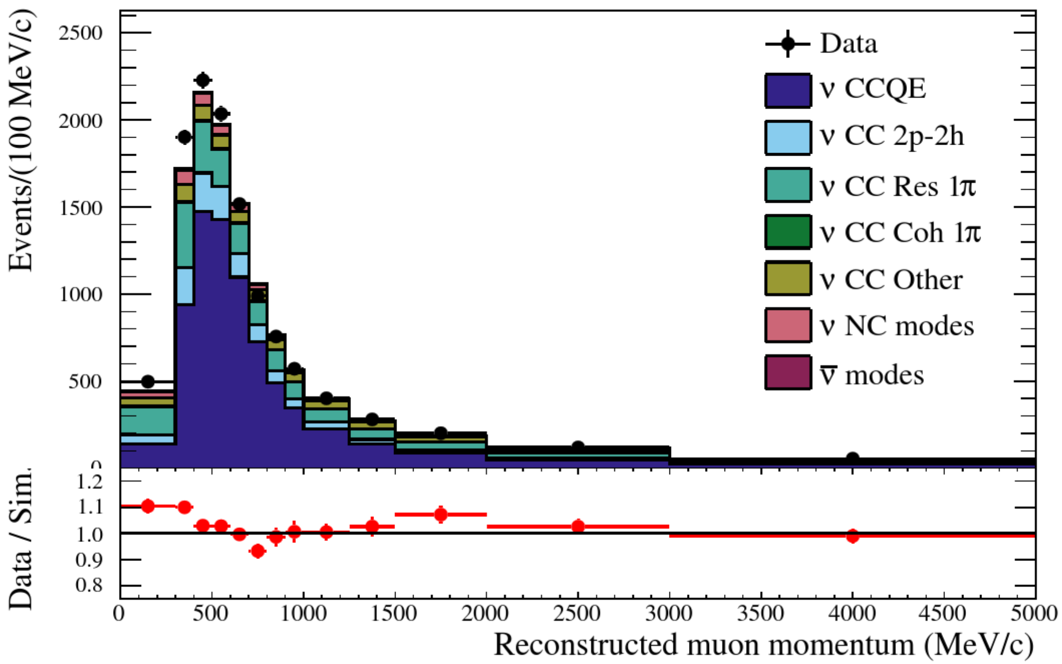
- Single pion pushed outside boundary: M_A^{RES} = 0.8 GeV
- Pion FSI parameters OK
- Detector parameters OK (not shown here)



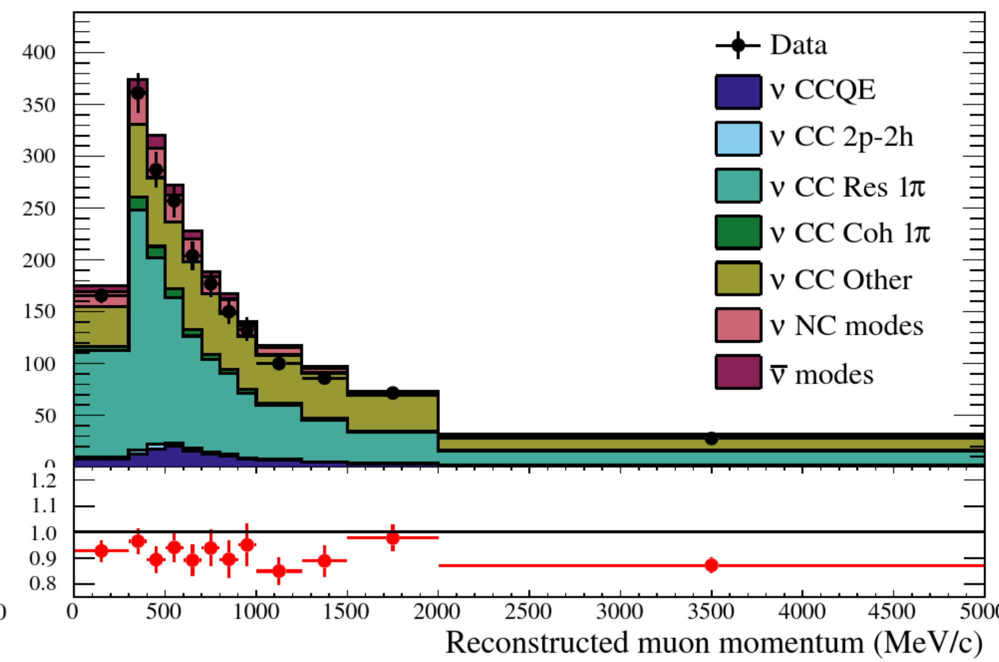
Some pre-fit plots

- Clear deficiencies across the samples
- Generally underestimate CC0π, overestimate CC1π

FGD1 CC0π FHC



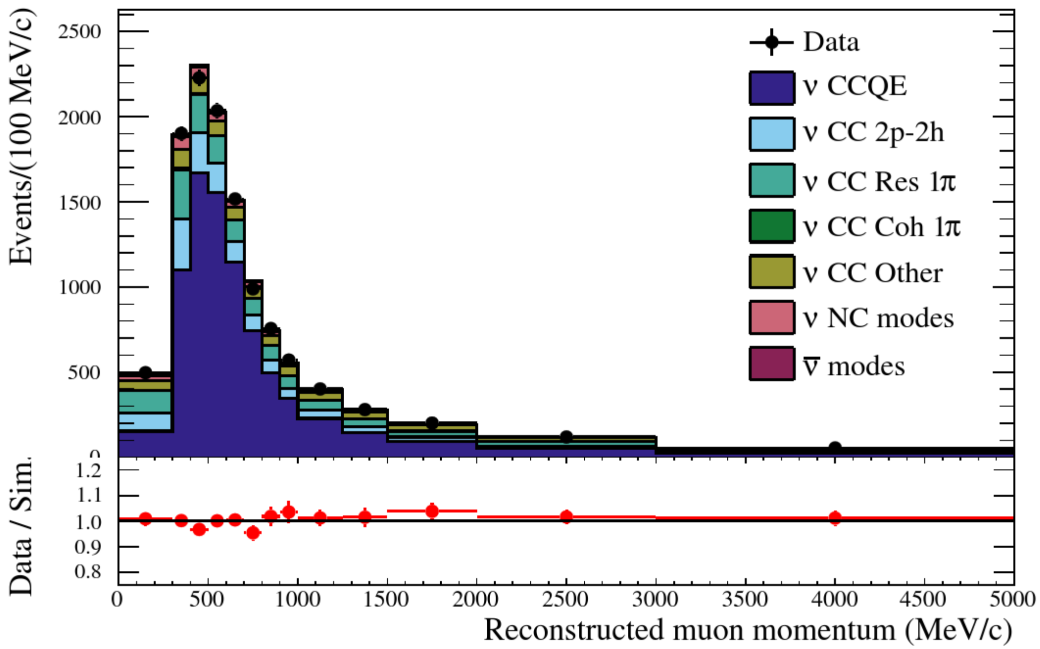
FGD1 CC1π FHC



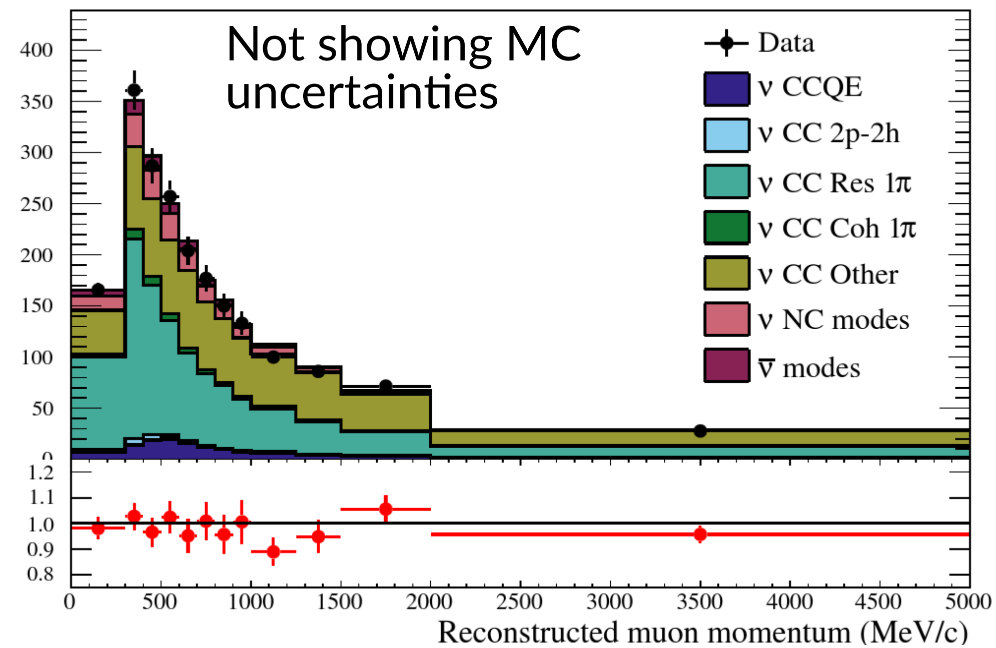
Some post-fit plots

- As expected we're not getting a perfect fit
  - Not templated as we're fitting theory parameters

FGD1 CC0π FHC



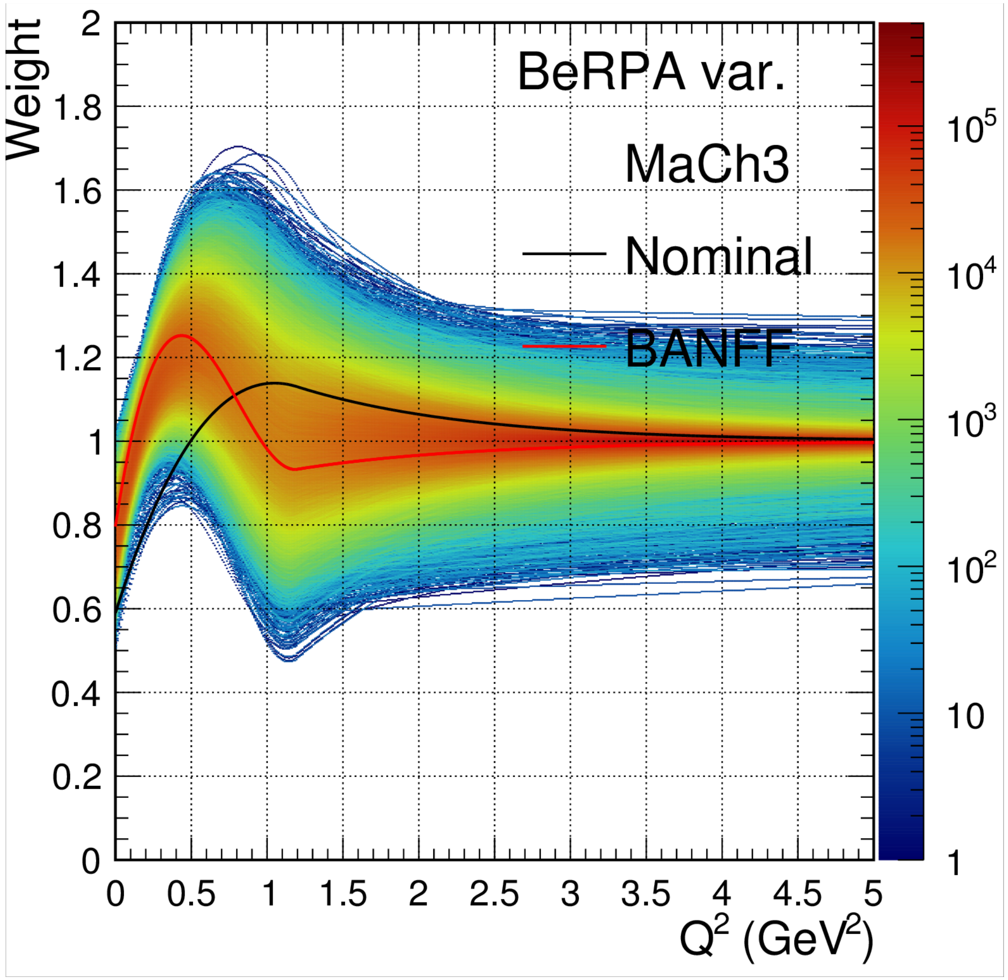
FGD1 CC1π FHC



- 2D distributions don't fit perfectly, notably for 1π and Other samples
  - 1π and multi-π modelling less sophisticated

Why is BeRPA pulled?

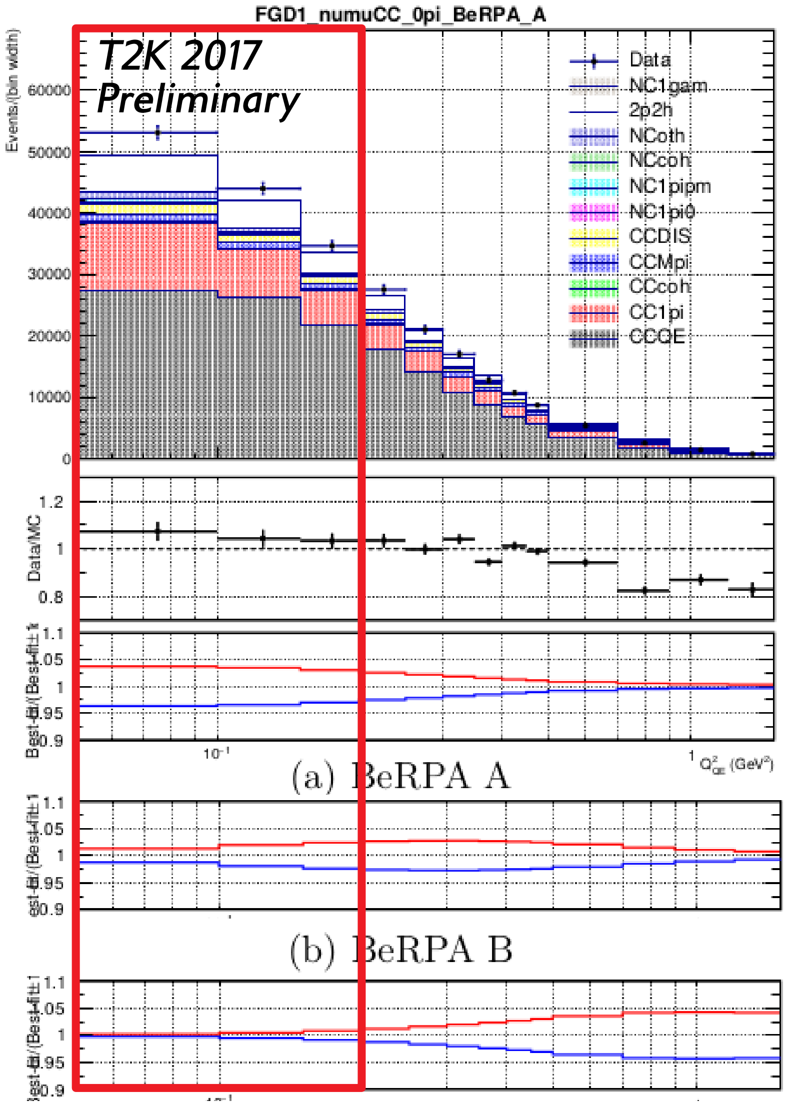
- RPA parameters are being pulled strongly in the fit

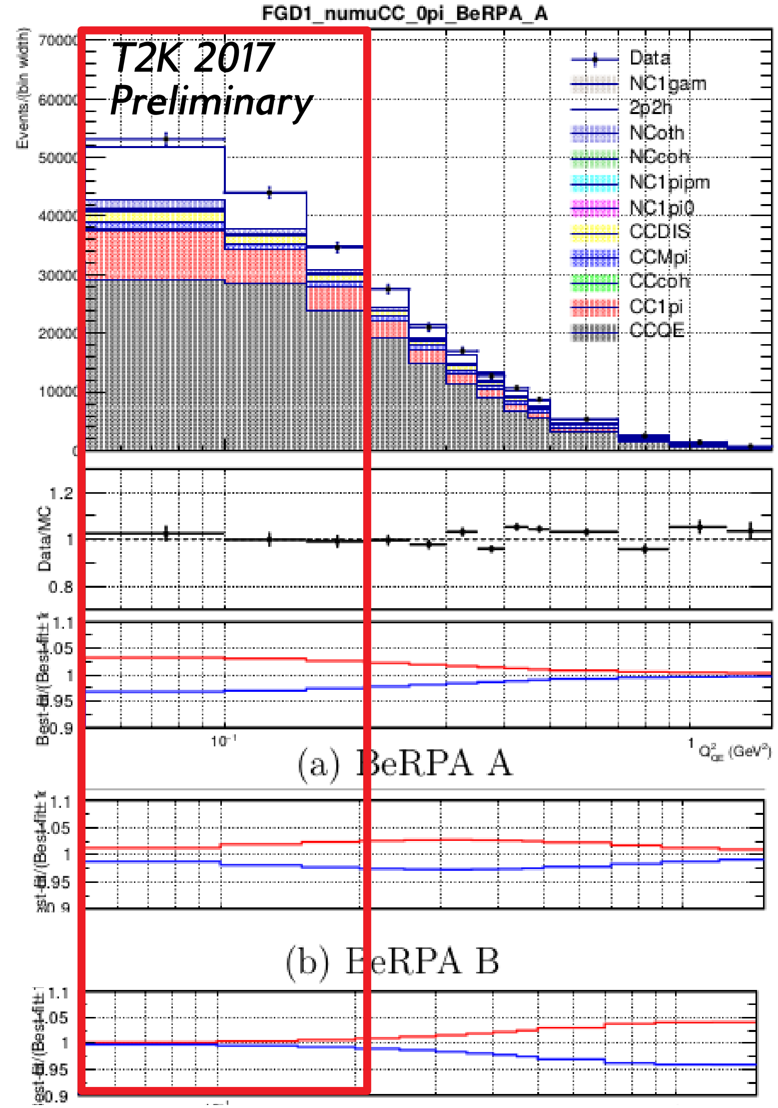


- Resulting RPA correction very non-Nieves
- True for both the frequentist and Bayesian analyses

Why is BeRPA pulled?

- Projecting onto "reconstructed" Q^2_{QE} (assuming CCQE kinematics)



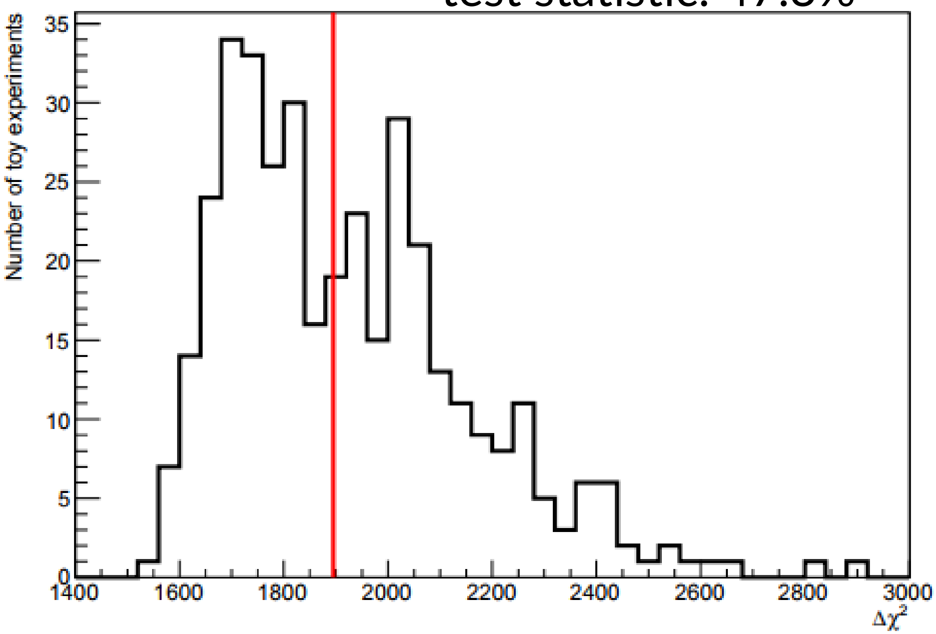


- Clear deficiency at low Q^2_{QE} for FGD1 and FGD2 CC0π selections
- BeRPA A and BeRPA B control this region → Pulled in fit

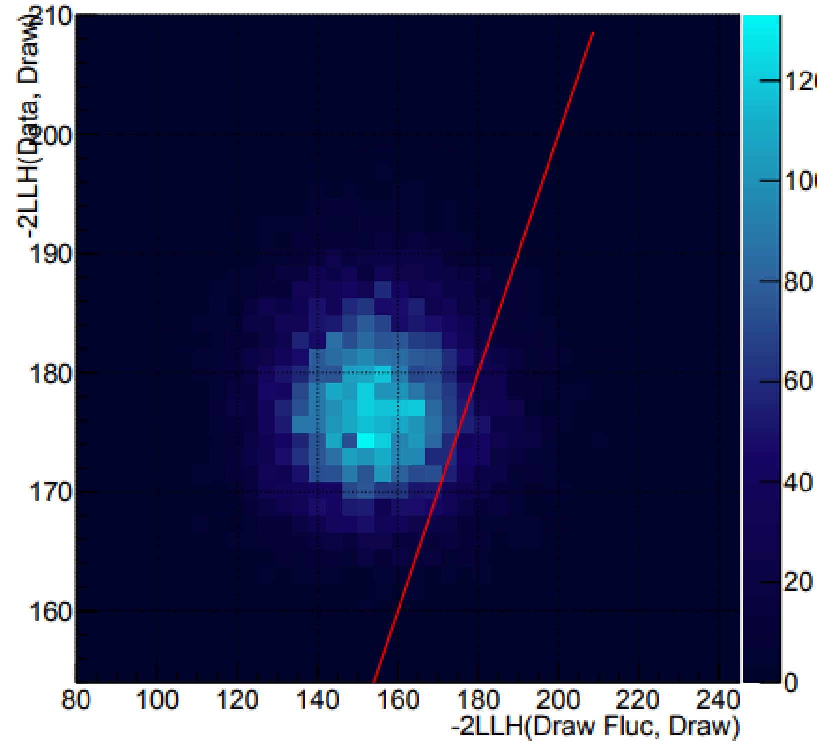
Post-fit evaluation

- Bayesian (MCMC) and Frequentist (Minuit) analyses for ND280-only
  - Propagate post-fit to SK as Gaussians from Frequentist analysis
  - Or fit ND280 simultaneously with SK data with MCMC
- P-value testing on the post-fit model
  - Decides if we abandon all hope and start from scratch

Frequentist p-value on total test statistic: 47.3%



Bayesian posterior predictive p-value, FGD2 CC0π: 10.9%

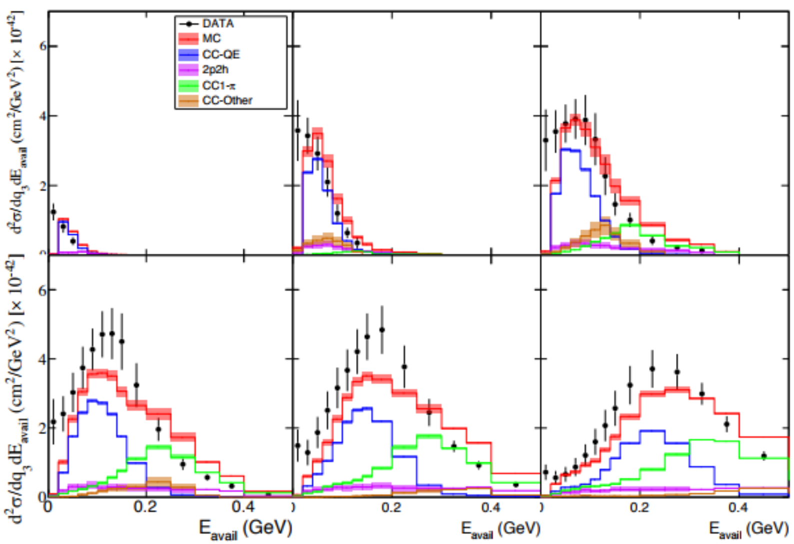


  - Not happened… yet!

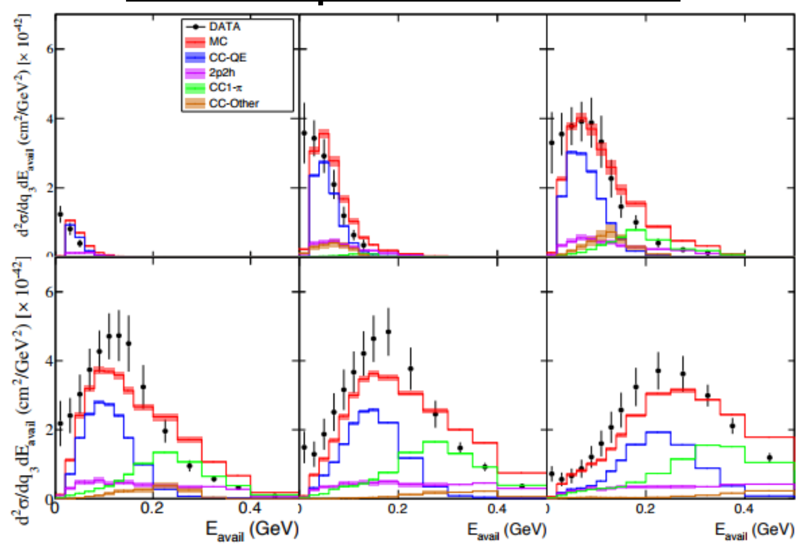
Post-fit evaluation

- Propagate cross-section constraints to external neutrino cross-section data
  - MINERvA CC-inclusive low recoil data worse post-fit

NIWG model 2015/6



ND280 post-fit 2015/6

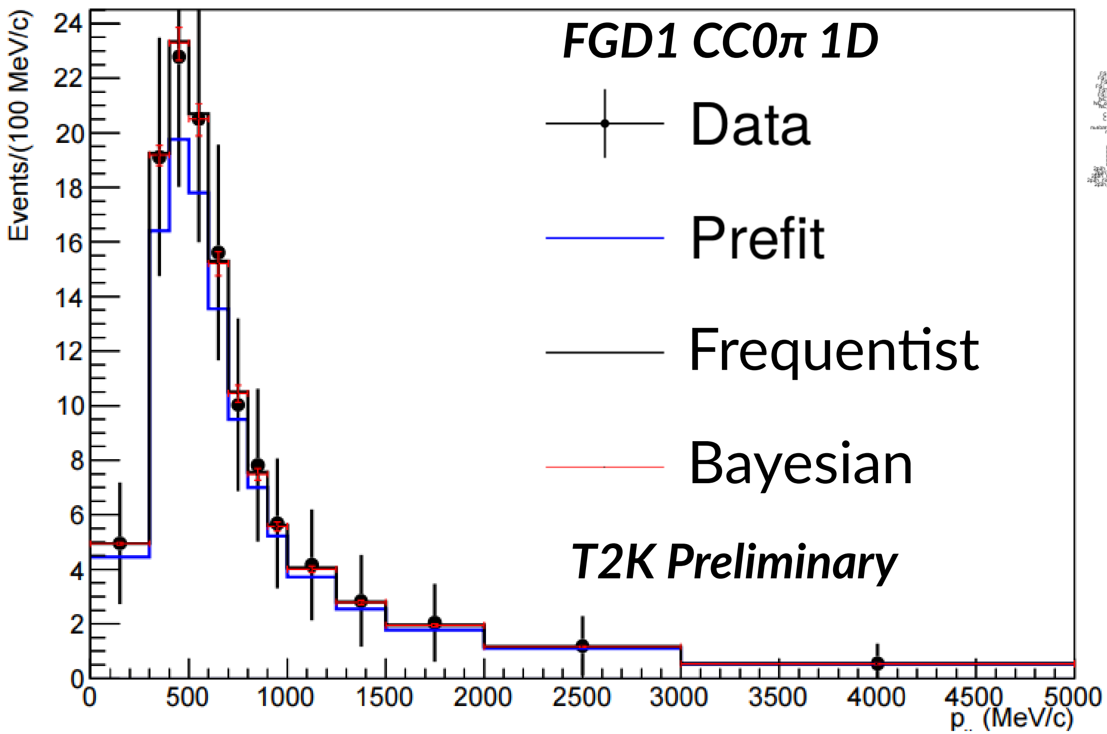


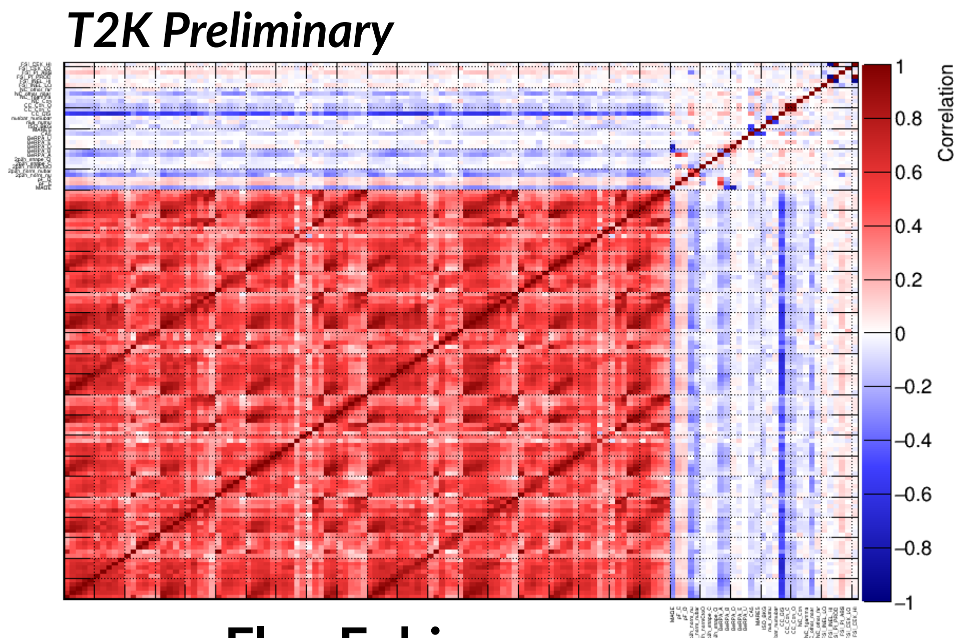
By Patrick Stowell

- Run large number of fake-data studies on plausible alternatives
  - How much do we bias oscillation parameters if model B is the perfect model but we're fitting using model A

Group comparisons

- Frequentist and Bayesian methods agree well





Flux E_ν bins

Cross-sections

- Post-fit correlations look reasonable (actually inspected in 2D)
  - Flux internally correlated and inversely correlated with cross-sections

To look forward to

- Double neutrino and anti-neutrino data at ND280 in the can
  - Very interesting to see how fit develops
  - Need to continue emphasis on nailing down systematics
- More ND280 selections—better topology separation
  - Larger acceptance at ND280, including backward going
  - CC0π, CC1π, CCOther selections for anti-neutrino
- More interaction model developments
  - New 1p1h model
  - New 2p2h model
  - New single pion model
  - New multi-pi/DIS model
  - New initial state model
- Large systematic reductions from the beam group
  - New NA61/SHINE T2K replica target data
- GENIE fits?

Summary

- T2K uses a near-detector fit to estimate systematics for oscillation analyses at SK
- Uses 14 topological samples at ND280 in (p_μ, $\cos\theta_\mu$)
- Rapidly moving cross-section model
- Some cross-section parameters move outside the conservative pre-fit 1σ prescription, flux and ND280 parameters well behaved
- Two methods of propagating ND280 result: assume Gaussianity or do a simultaneous ND280 and Super-K fit
- More data in the can with new selections and systematics coming up

Thank you!

Likelihood

- Sample statistics modelled as Poisson
- Nuisance parameters as Gaussians or flat

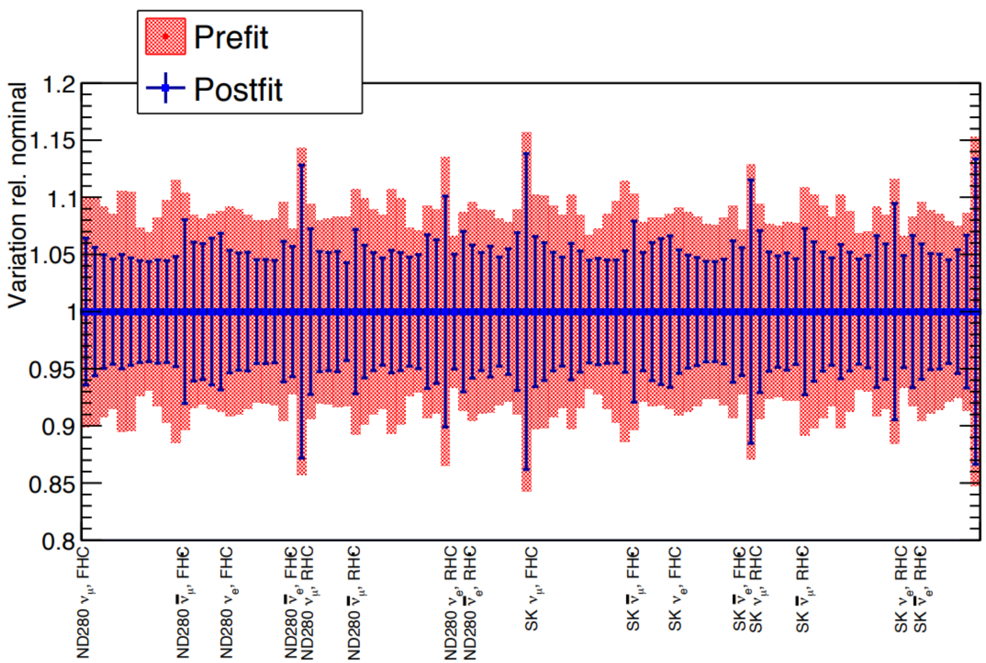
$$-\log \mathcal{L}_{\text{Total}} = \sum_{\text{Bins}} \left[\underbrace{\lambda(\vec{\theta})}_{\text{MC}} - \underbrace{n}_{\text{Data}} + n \log \frac{n}{\lambda(\vec{\theta})} \right] + \sum_{\text{Systematics}} \frac{1}{2} \left[(X_i - \mu_i) (\mathbf{V})^{-1}_{ij} (X_j - \mu_j) \right]$$

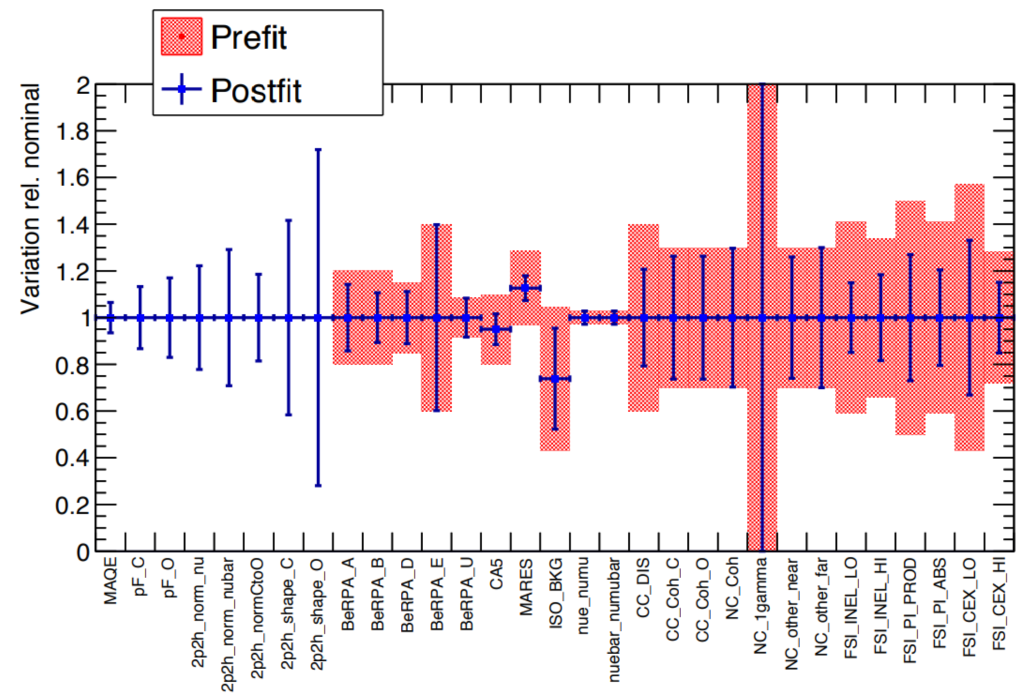
Systematic *i* with value *X* and prior *μ*, with covariance *V*

- About 750 parameters at ND280
- 12 selections at ND280, about 120 bins/selection
  - 1400 fitting bins in p_μ $\cos\theta_\mu$, 556 detector bins

2017 Asimov fits

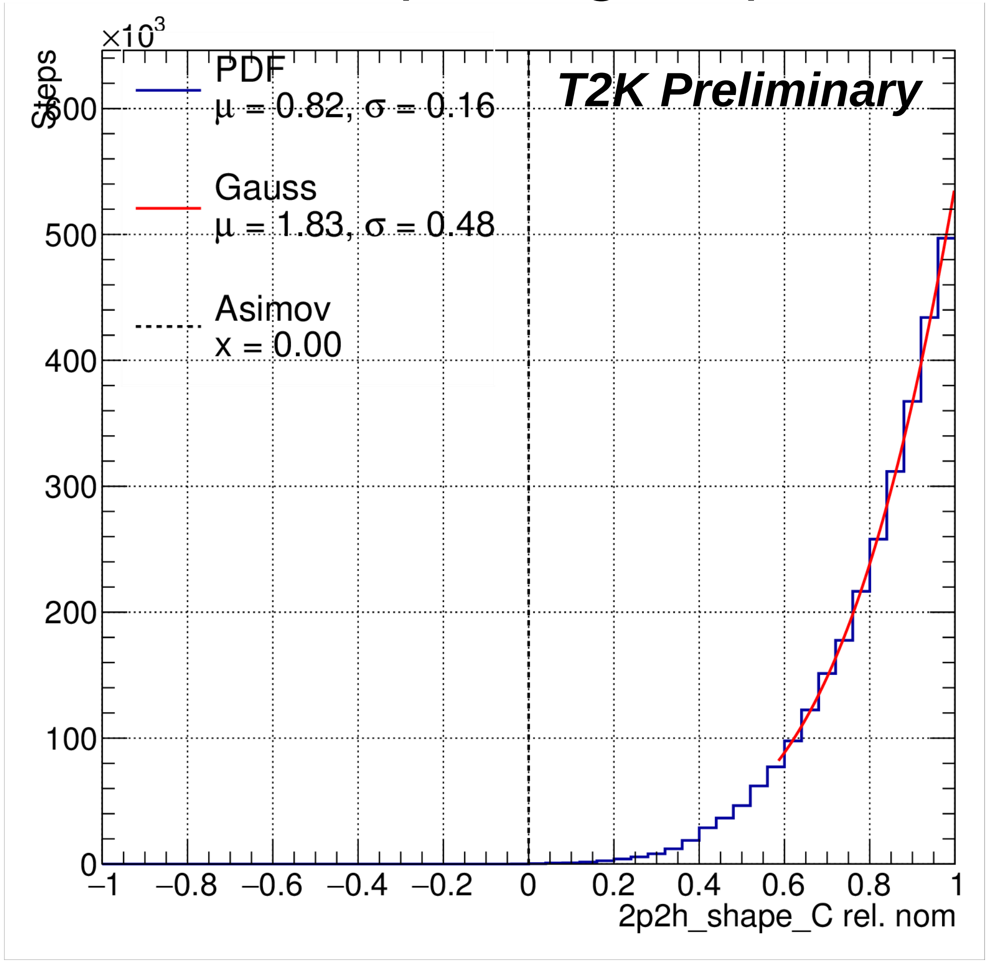
- Asimov/closure fits show no surprises

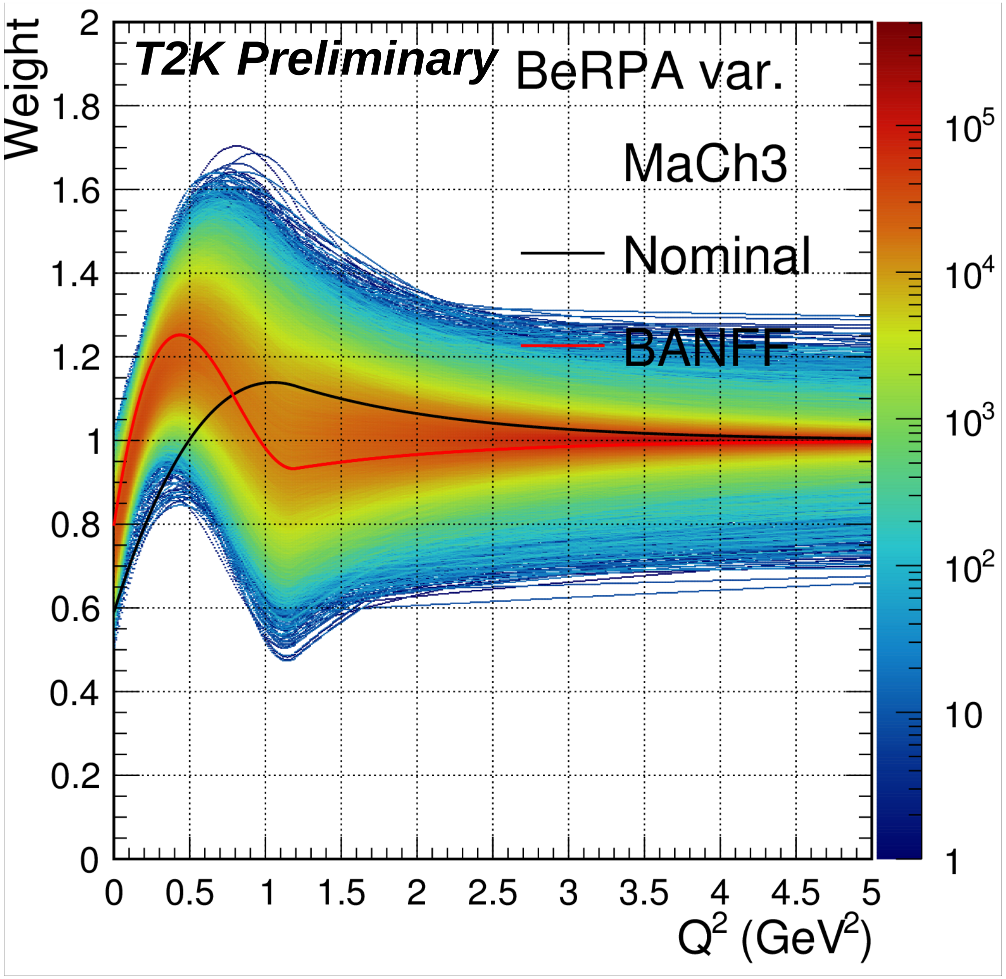




2017 ND280 data fits

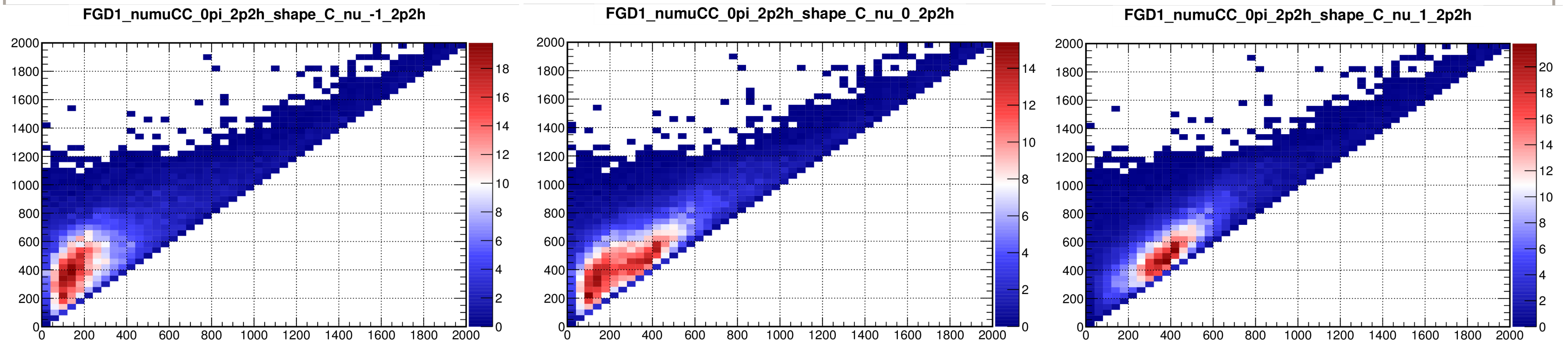
- Looking closer at cross-section parameters
- See large changes for BeRPA and 2p2h shape
  - Are we pushing the parameterisation too far?





2p2h shape

- Have Nieves 2p2h with leptonic tensor in NEUT
- No method of varying parameter other than normalisation
- Assume PDD-like (+1), non-PDD-like (-1), nominal shape: transition between them without interference terms in q_0 q_3 space



- Realistically only covers Nieves 2p2h without any interferences
  - Not covering Martini 2p2h, SUSA, SF, etc
- Martini covered by fake-data analyses at SK and inflating parameter errors

Cross-section systematics

- 2017 analysis used 31 cross-section parameters

	Parameter	Nominal	Error	Prior	Type	Comment
CC0π	CCQE model	2	N/A	N/A	D	MDLQE = 2 corresponds to the RFG model.
	SF→RFG	1	N/A	N/A	D	
	M_A^{QE} (GeV)	1.21	0-10	flat	B	
	M_A^{QE} $\bar{\nu}$-H (GeV)	1.03	0	N/A	D	
	p_F ^{12}C (MeV)	217	31	flat	B	
	p_F ^{16}O (MeV)	225	31	flat	B	
	2p2h norm. ν–^{12}C	1	1	flat	B	
	2p2h norm. $\bar{\nu}$–^{12}C	1	1	flat	B	
	2p2h norm. ^{12}C to ^{16}O	1	0.2	flat	B	
	2p2h shape ν–^{12}C	0	1	flat	B (or N)	
	2p2h shape ν–^{16}O	0	1	flat	B (or N)	30% correlated with 2p2h shape ν–^{12}C
	BeRPA A	0.59	0.118	gauss.	B	
	BeRPA B	1.05	0.21	gauss.	B	
	BeRPA C	1.13	0.17	gauss.	B	
	BeRPA D	0.88	0.352	gauss.	B	
	BeRPA U	1.2	N/A	N/A	D	
RES	$M_A^{1\pi}$	1.07	0.15	gauss.	B	correlations in Fig. 48
	C_5^A	0.96	0.15	gauss.	B	correlations in Fig. 48
	$I = 1/2$ Bkg.	0.96	0.40	gauss.	B	correlations in Fig. 48
Other	CC coh. norm. ^{12}C	reweight	0.3	gauss.	B	E_π weights are applied according to Table 12.
	CC coh. norm. ^{16}O	E_π weights	0.3	gauss.	B	Fully correlated with ^{12}C
	CC other shape	0.0	0.4	gauss	B	
	NC coh. norm.	1.0	0.3	gauss.	B	
	NC 1γ	2.0	2.0	gauss.	B	
	NC Other	1.0	0.3	gauss.	N,F	The NC other dial is treated separately at the near and far detectors.
	CC ν_e/ν_μ	1.00	$\sqrt{2} \times 0.02$	gauss.	F	2% anticorrelation between these two dials Sec. 7
	CC $\bar{\nu}_e/\bar{\nu}_\mu$	1.00	$\sqrt{2} \times 0.02$	gauss.	F	
Pion FSI					N,F	see Sec. 5

ND280 systematics

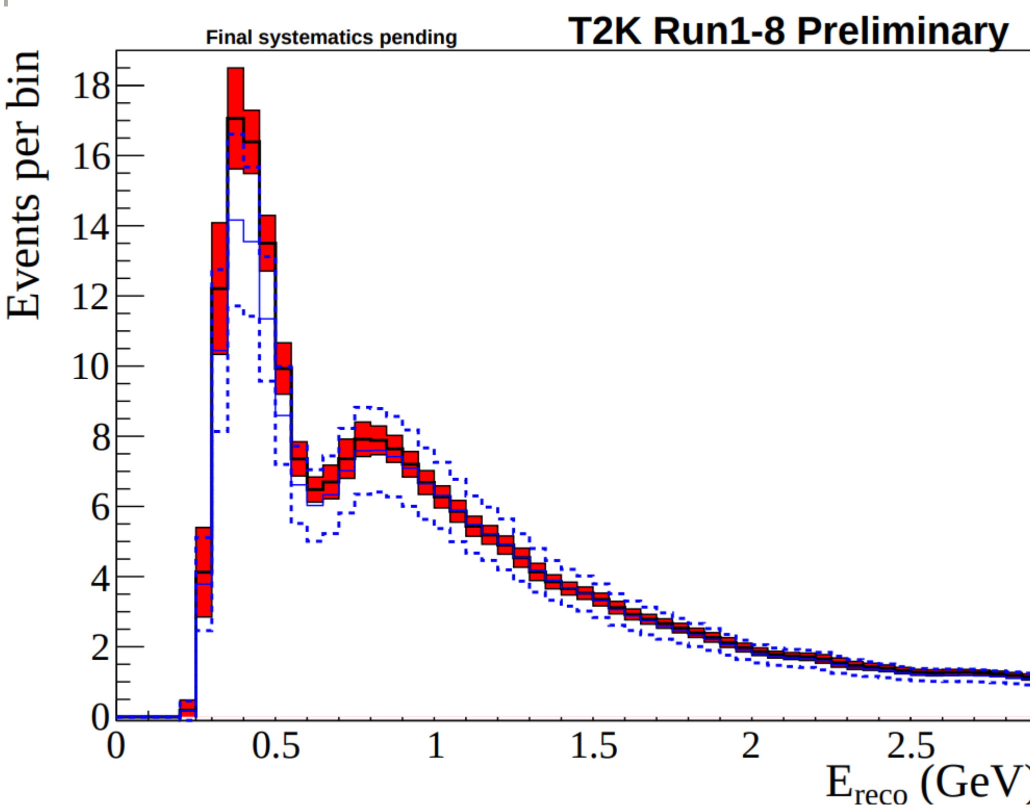
- Variation systematics
  - Have the ability to migrate events between selections
- B-field distortion
- TPC Momentum scale
- TPC Momentum resolution
- TPC PID
- FGD PID
- ToF resolution (FGD1-FGD2)
- ECal Momentum scale (barely used)
- ECal Momentum resolution (barely used)

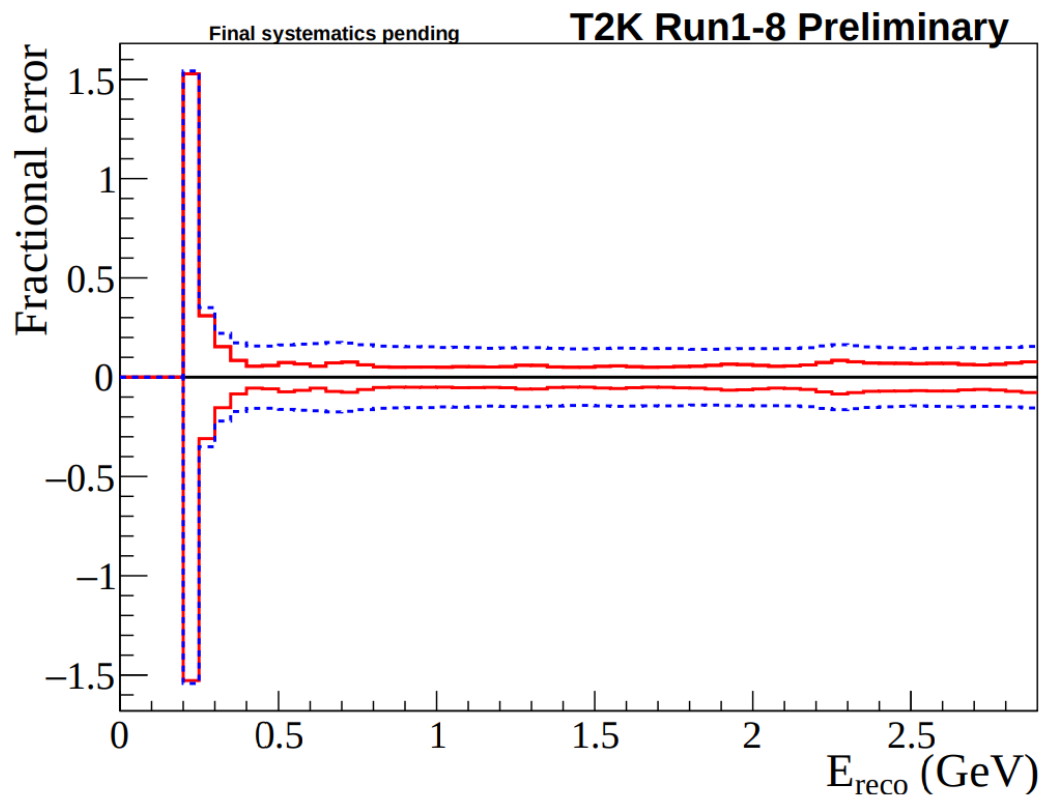
ND280 systematics

- Weight systematics: Simple normalisation systematics
- Michel electron efficiency
- TPC cluster efficiency
- TPC and FGD track efficiency
- FGD hybrid track efficiency
- FGD-TPC matching efficiency
- Pile-up
- FGD mass
- Out of fiducial volume
- Sand muon
- Pion and proton secondary interactions

Error envelopes

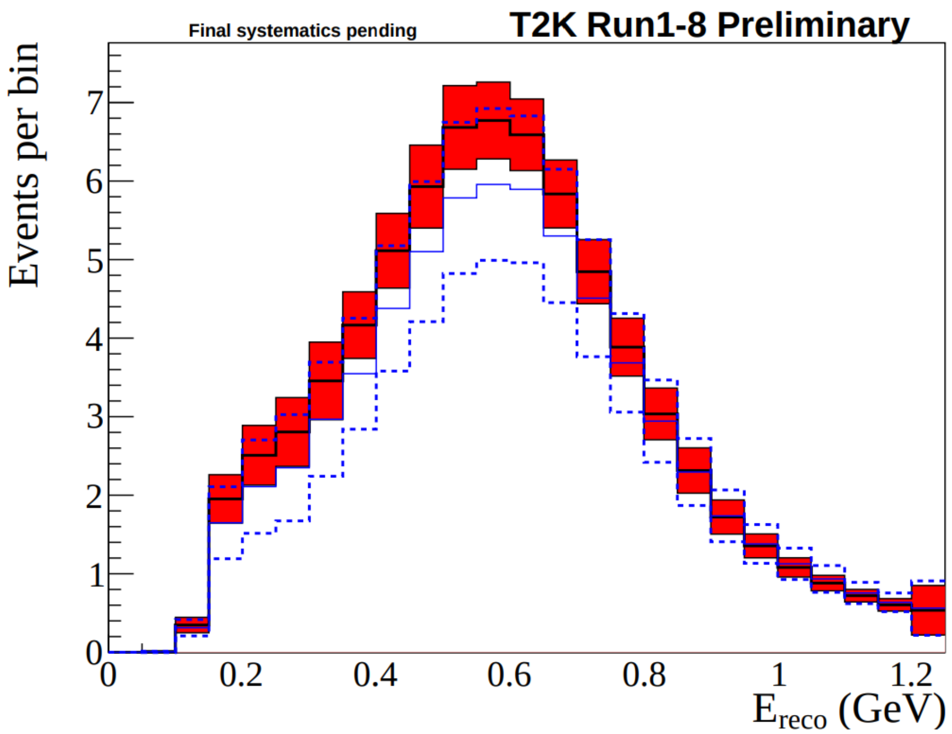
FHC ν_μ CC0π

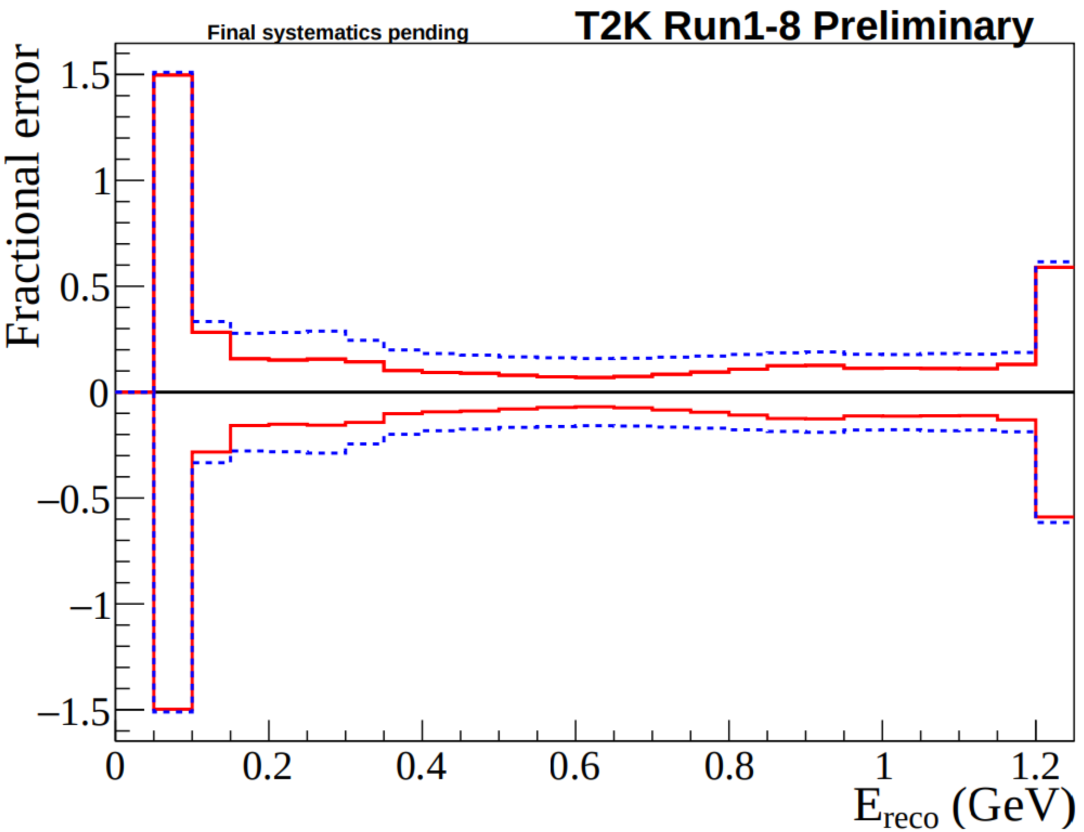




Error envelopes

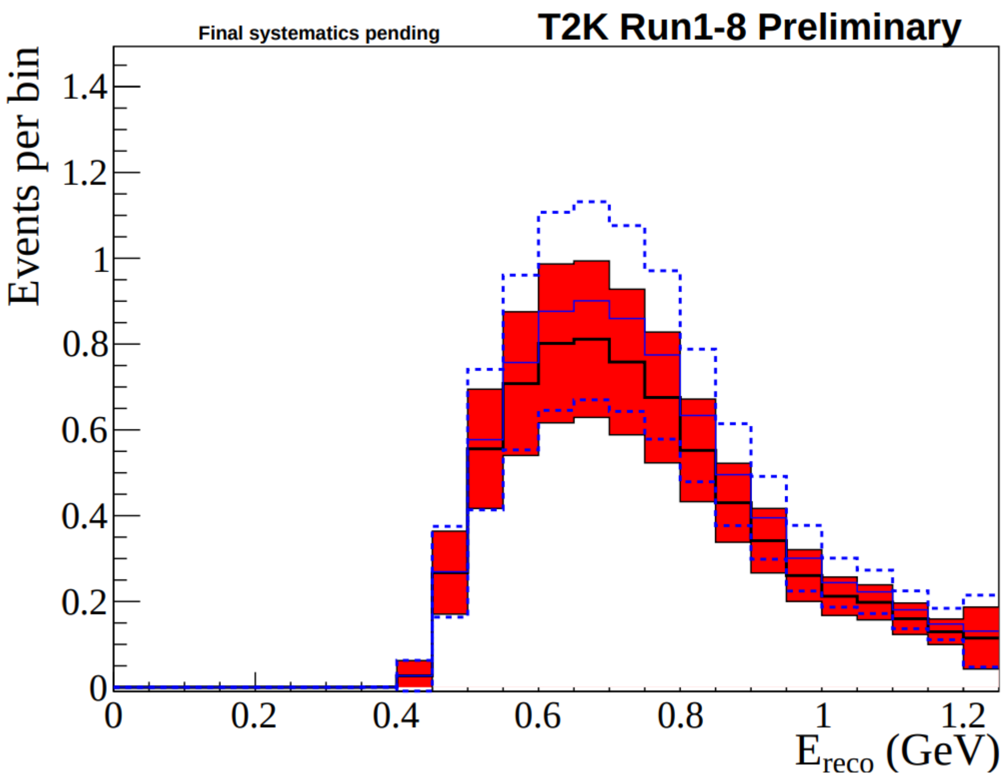
FHC ν_e CC0π

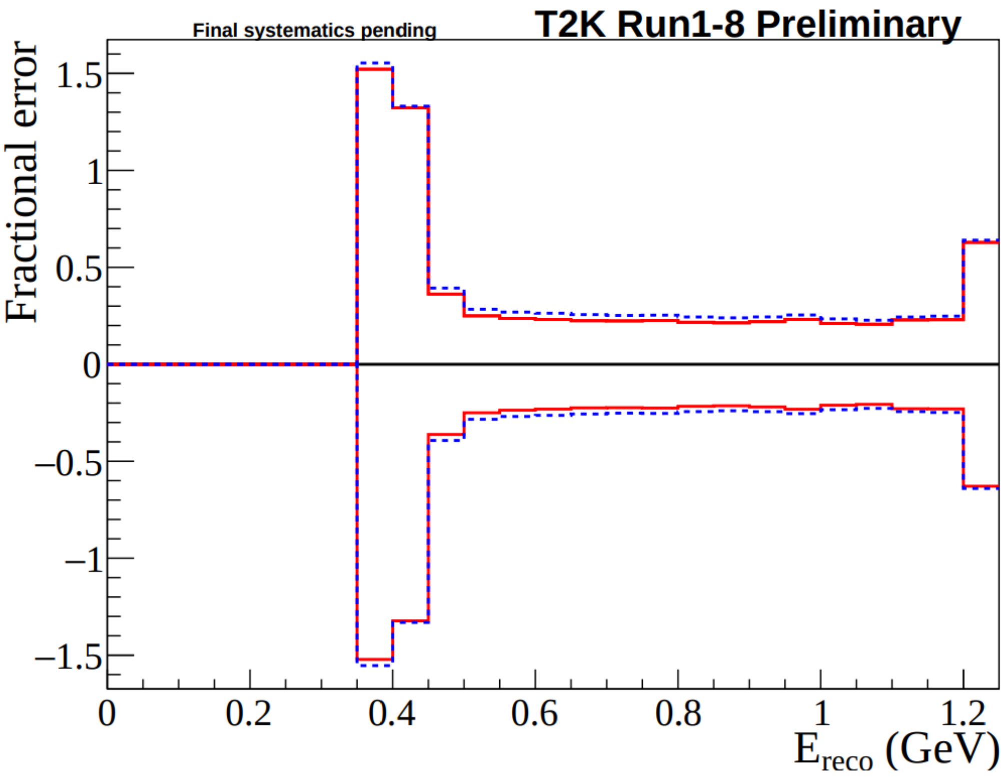




Error envelopes

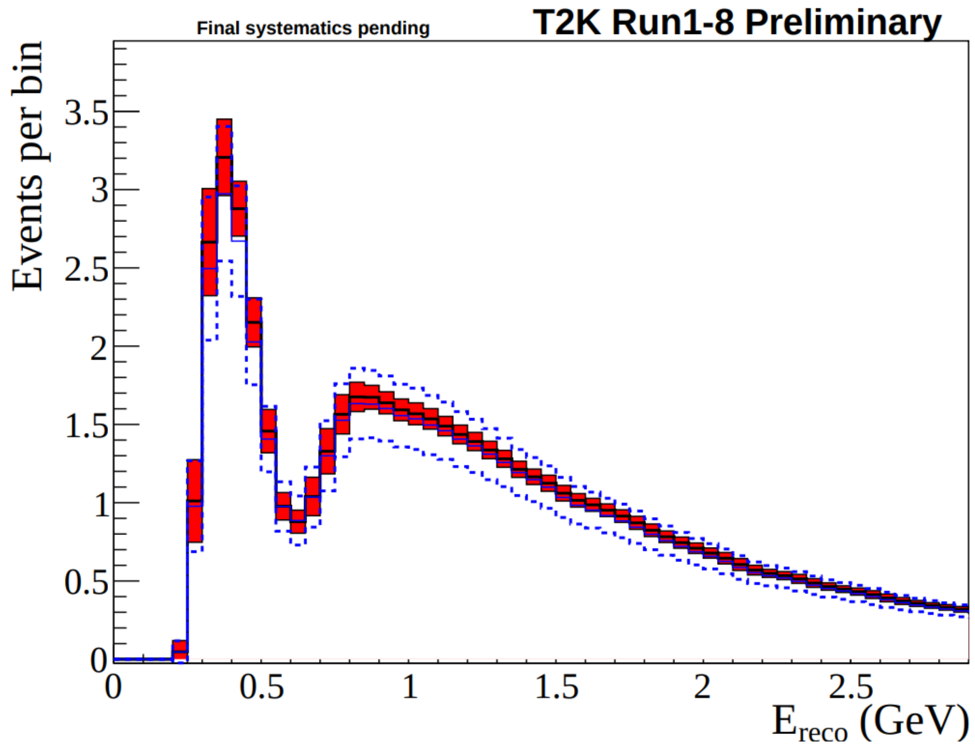
FHC ν_μ CC0π 1 decay e

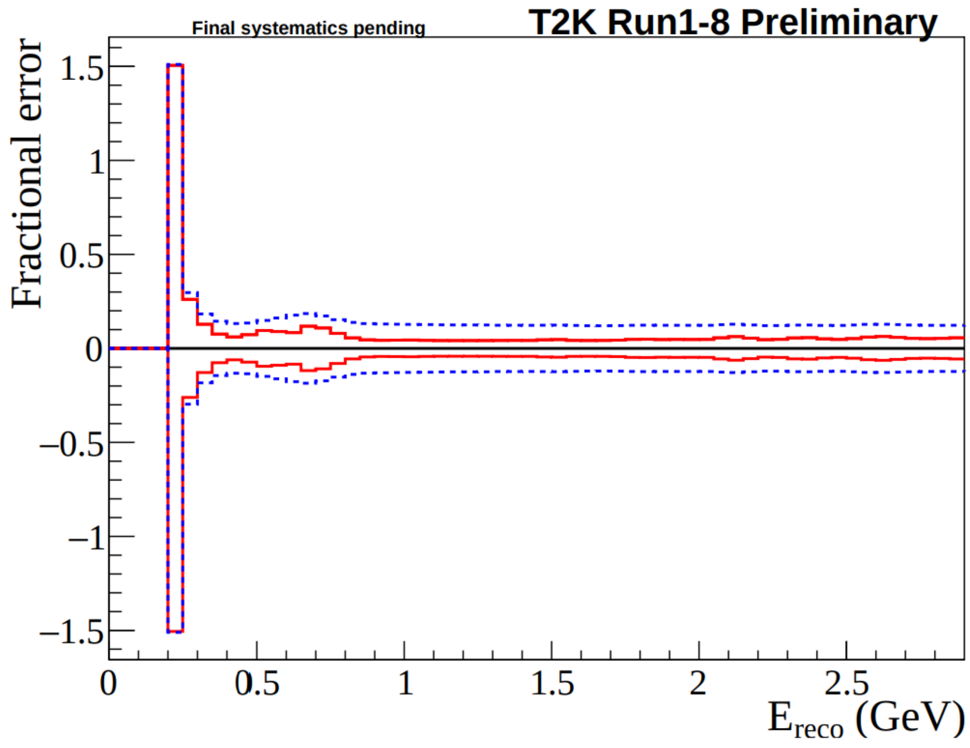




Error envelopes

RHC ν_μ CC0π





Error envelopes

RHC ν_e CC0π