Markov Chain Monte Carlo Oscillation Fits

(with an emphasis on systematics)

Asher Kaboth

2017.04.19

ROYAL HOLLOWAY UNIVERSITY OF LONDON

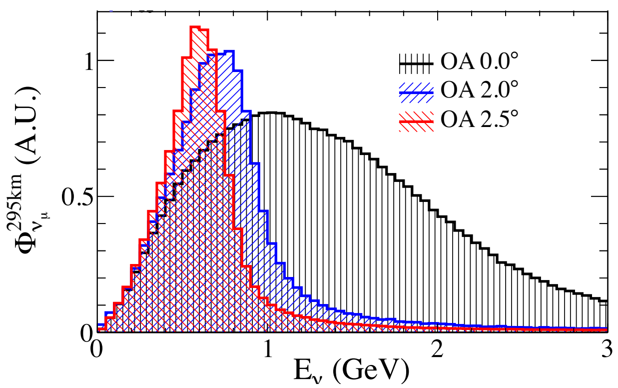
T2K

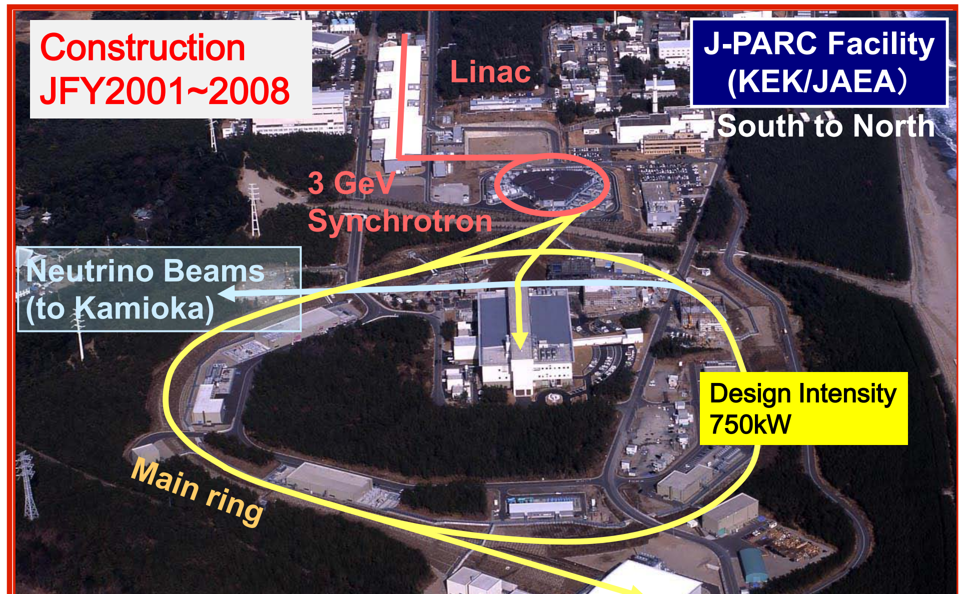
Outline

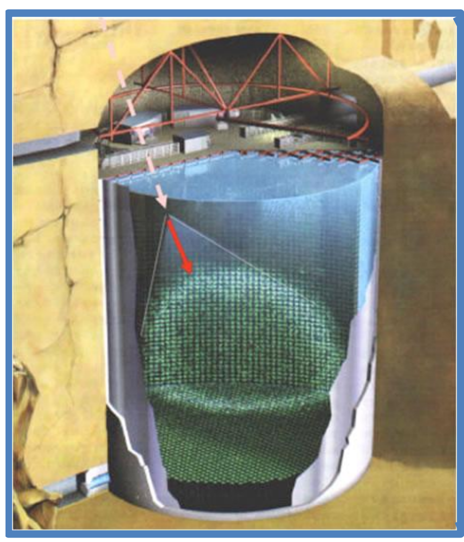
- Basics of T2K and MCMC
- Lessons learned from fits
- The importance of fake data fits
- Near-term future work

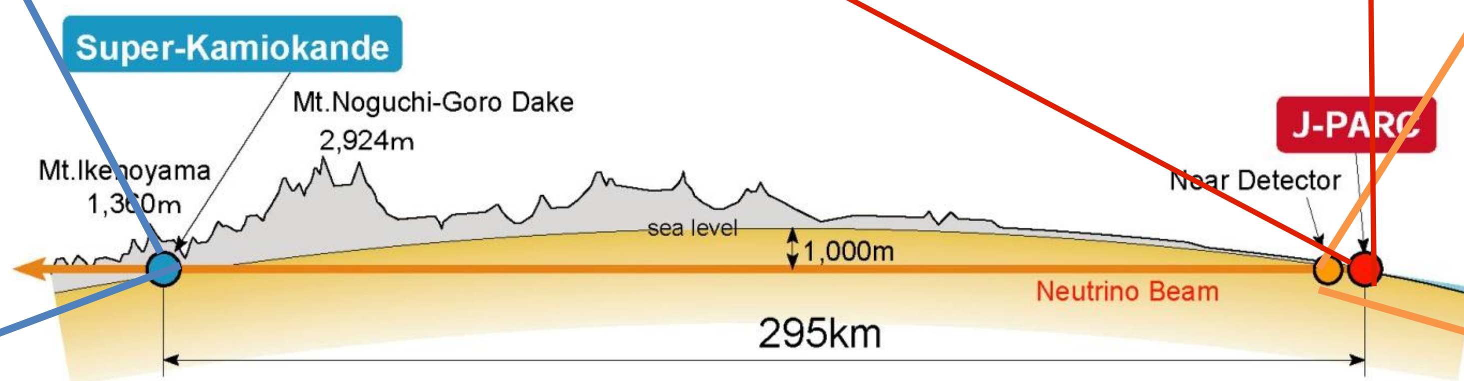
T2K

11 countries
59 institutions
~500 people

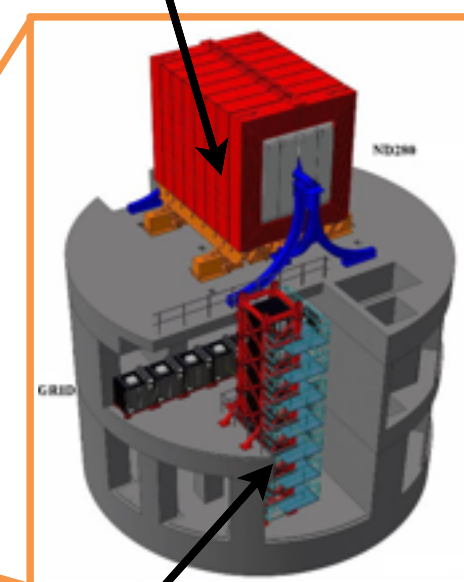








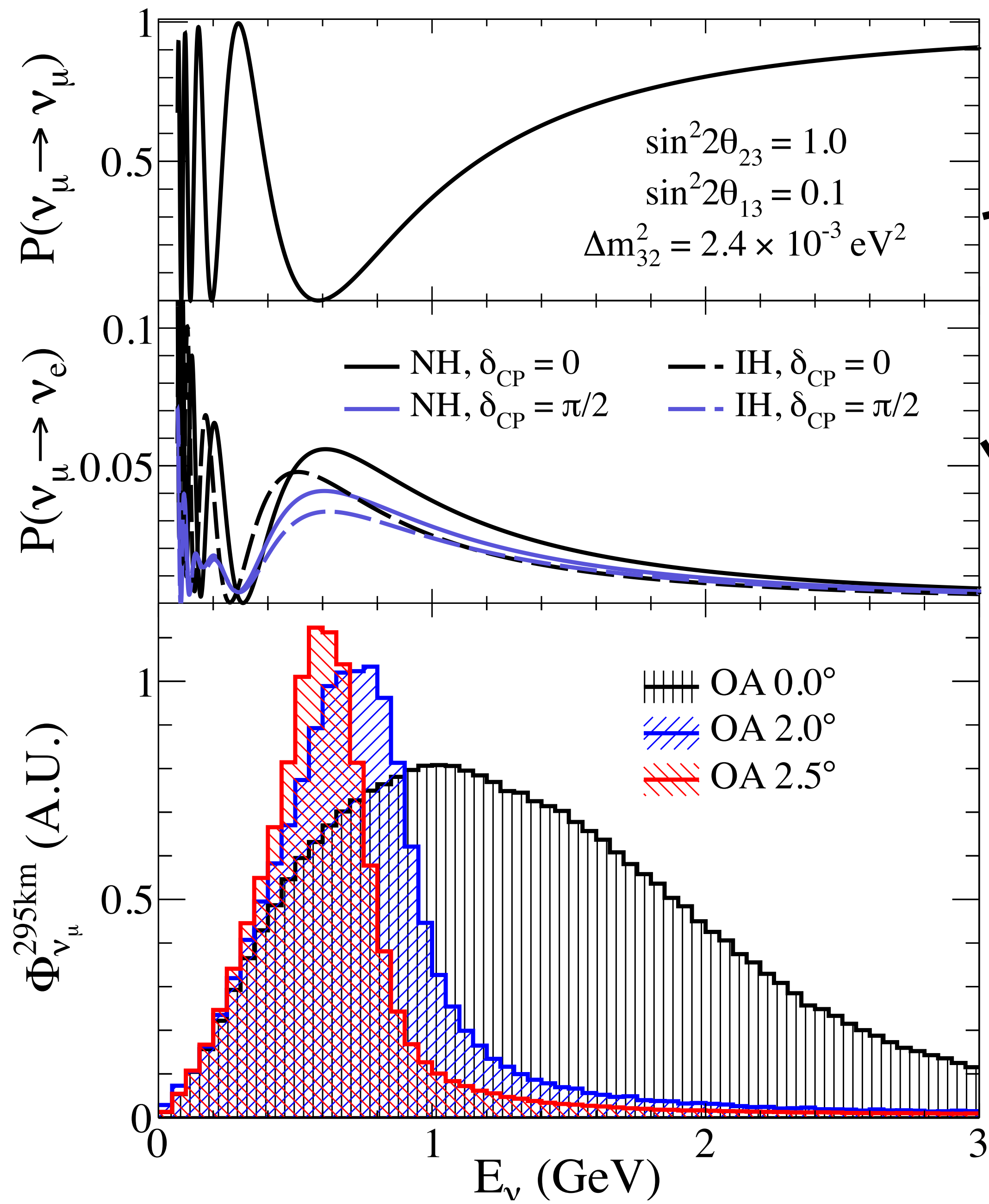
ND280

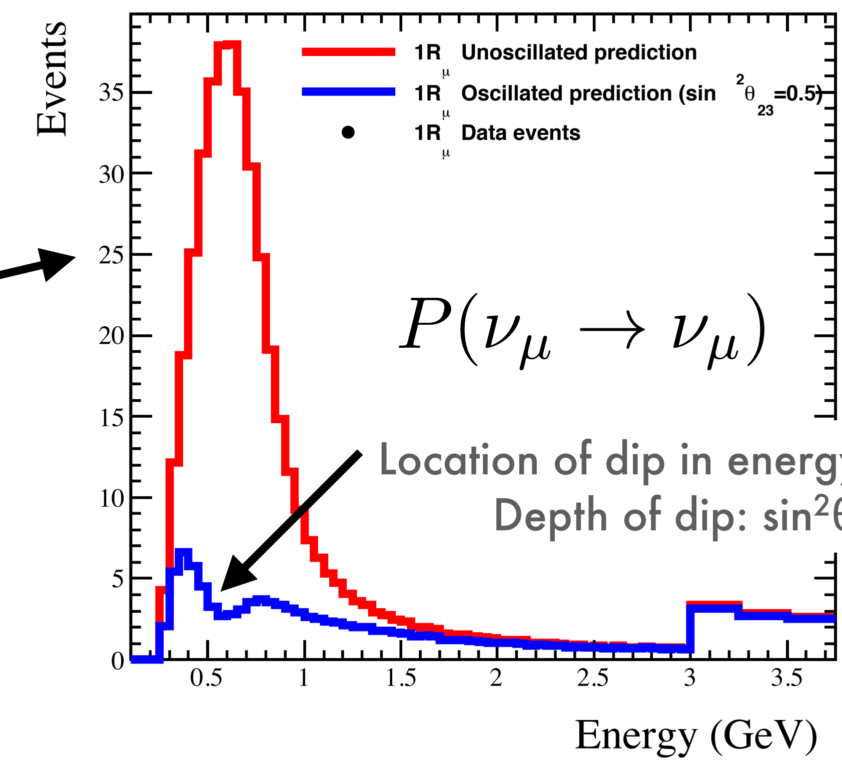


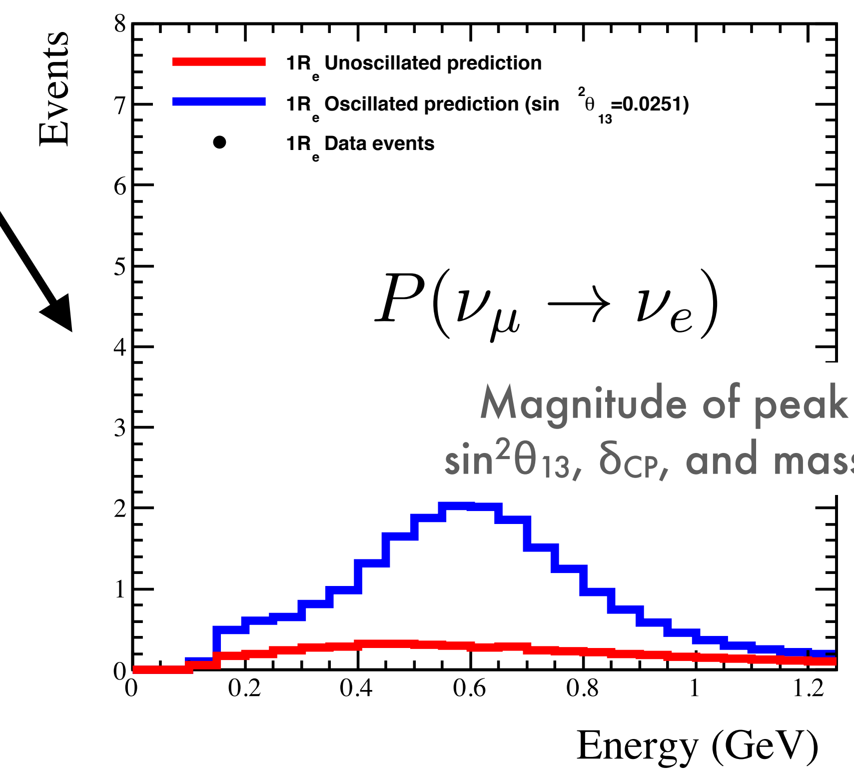
INGRID

All results are data from
Sept 2010–May 2013

Long Baseline Neutrino Oscillation



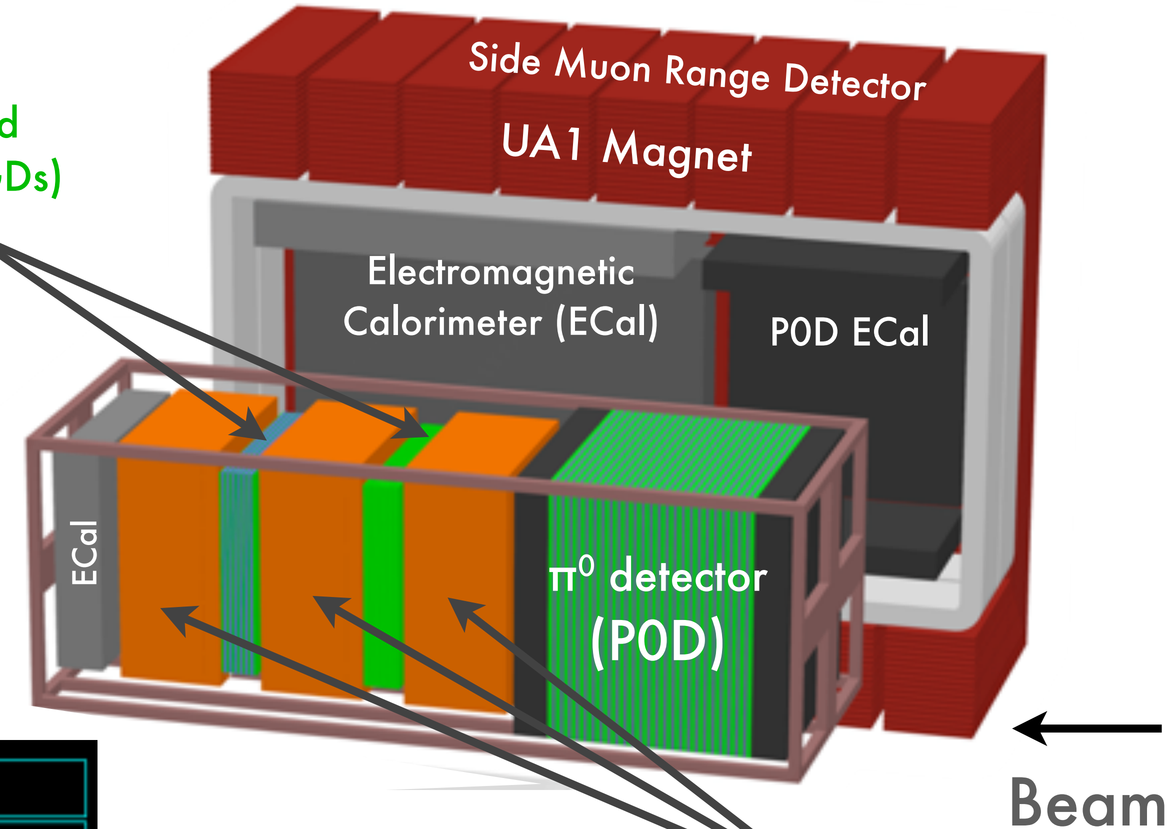


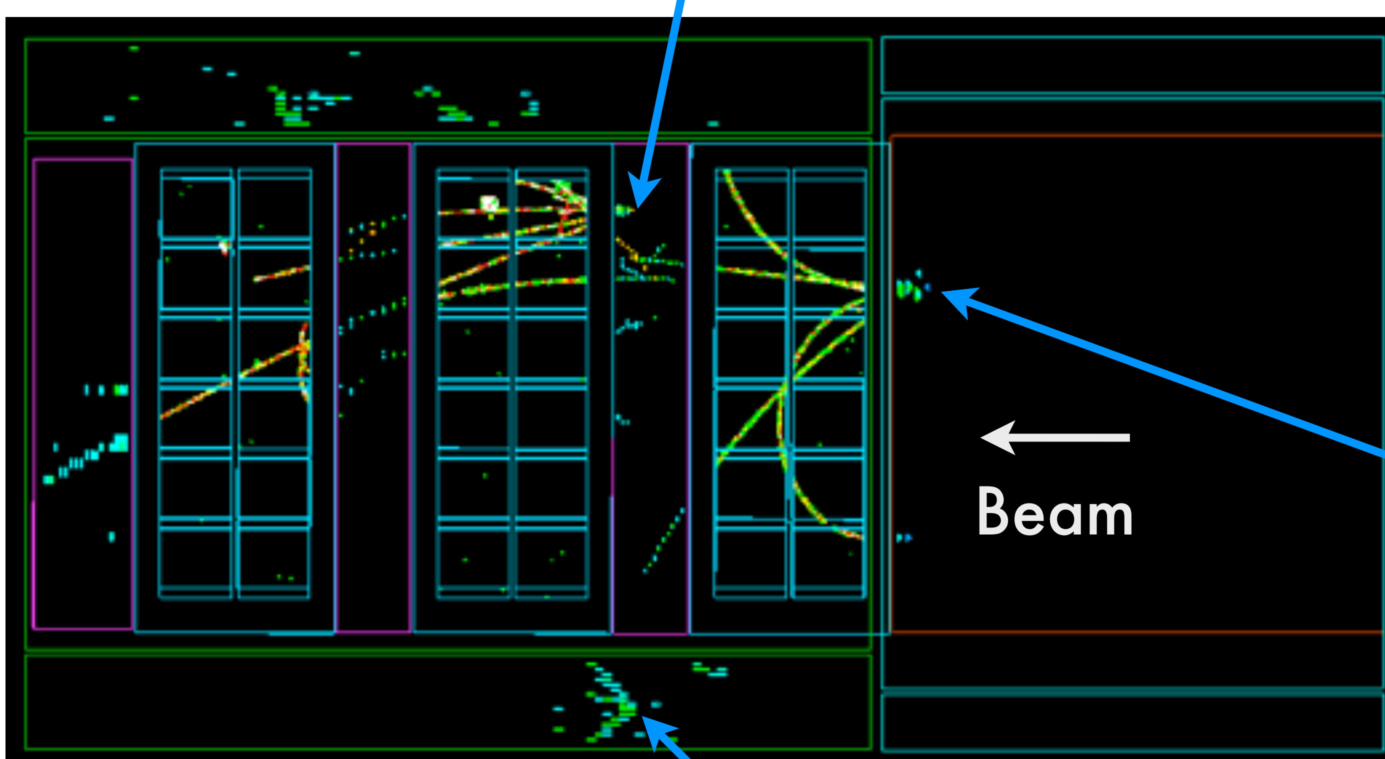


T2K Off-Axis Near Detector

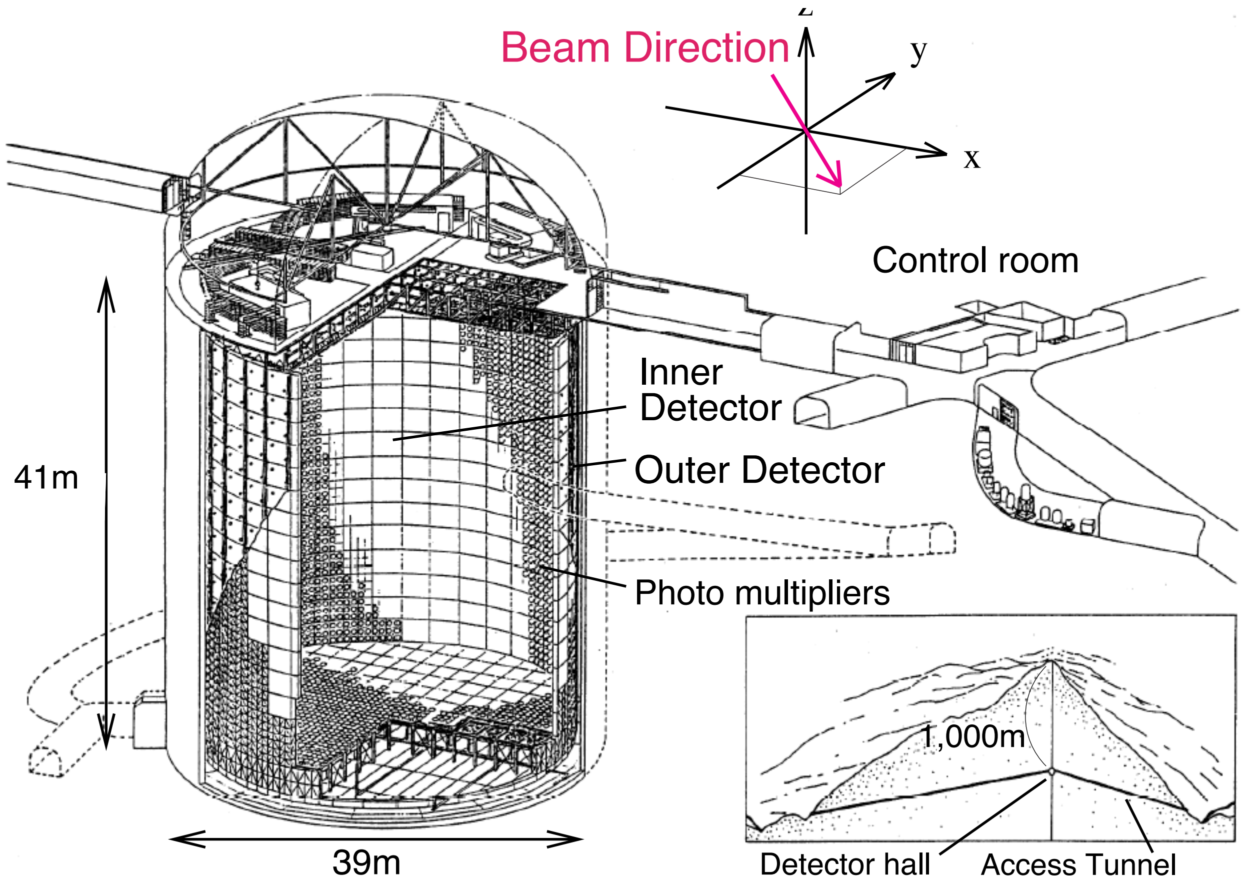
Primary Interaction Material: Carbon

Secondary Interaction Materials: Oxygen, Lead, Brass, Argon

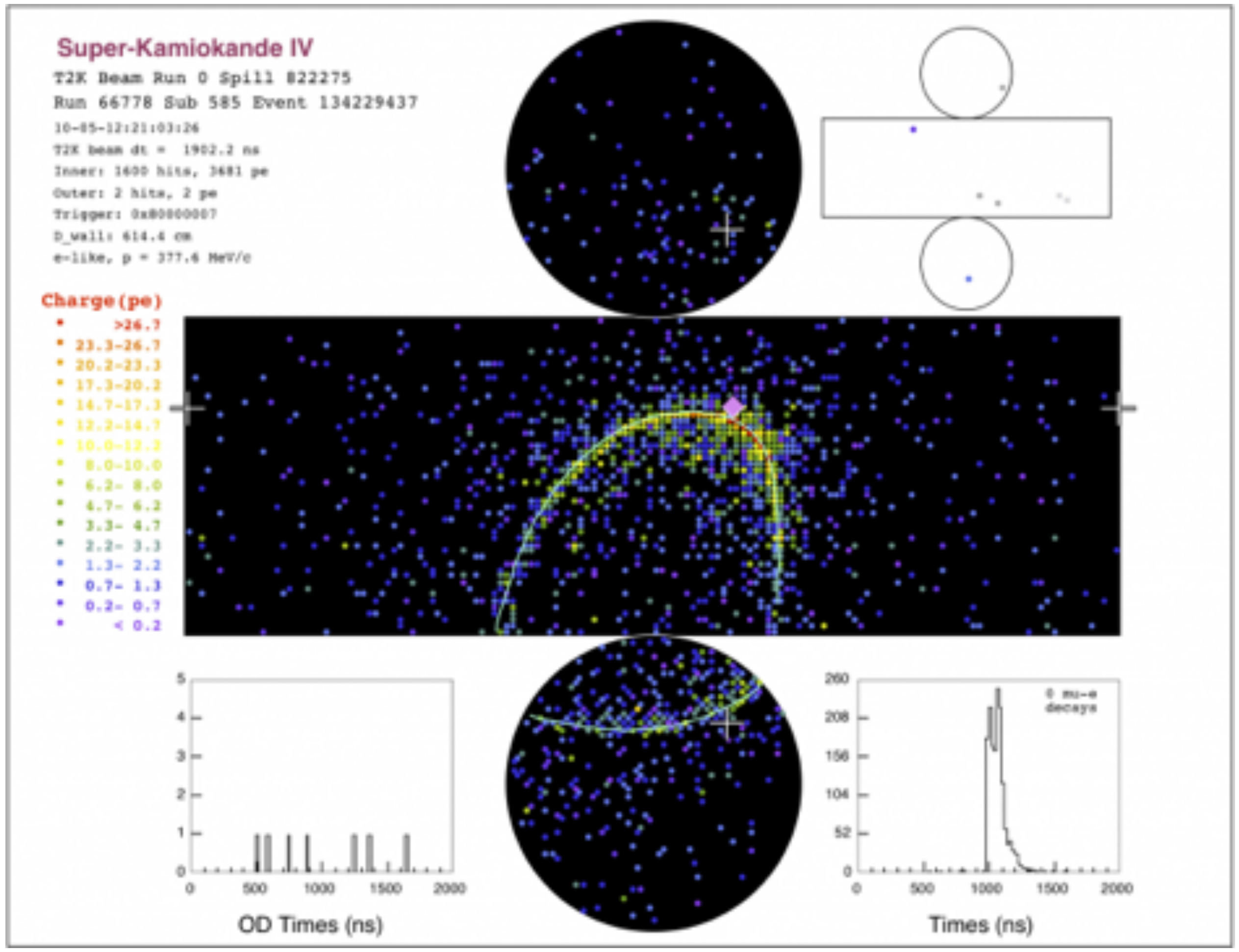


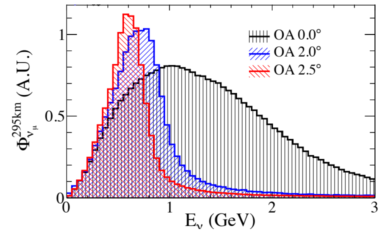


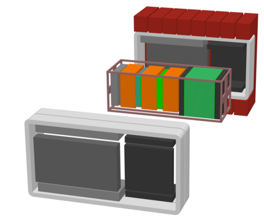
T2K Off-Axis Far Detector



Primary Interaction Material: Oxygen



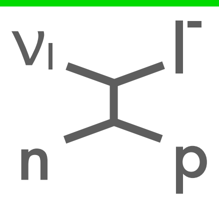


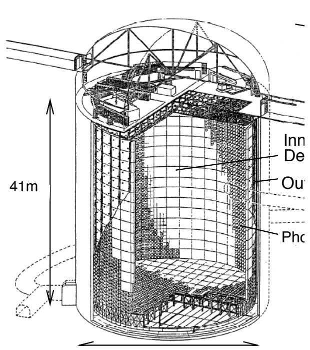


NA61/SHINE Data → Flux Model

INGRID/Beam Monitor Data → Flux Model

External Cross Section Data → Cross Section Model





ND280 Detector Model

ND280 Data

SK Data

SK Detector Model

Flux Model, Cross Section Model, ND280 Detector Model, ND280 Data, SK Data, SK Detector Model → Oscillation Fit → Oscillation Parameters

Fit near detector data, far detector data, and model constraints from external and internal data

Posterior Probability

$$P(\vec{z}|\text{data}) \propto P(\text{data}|\vec{z})P(\vec{z})$$

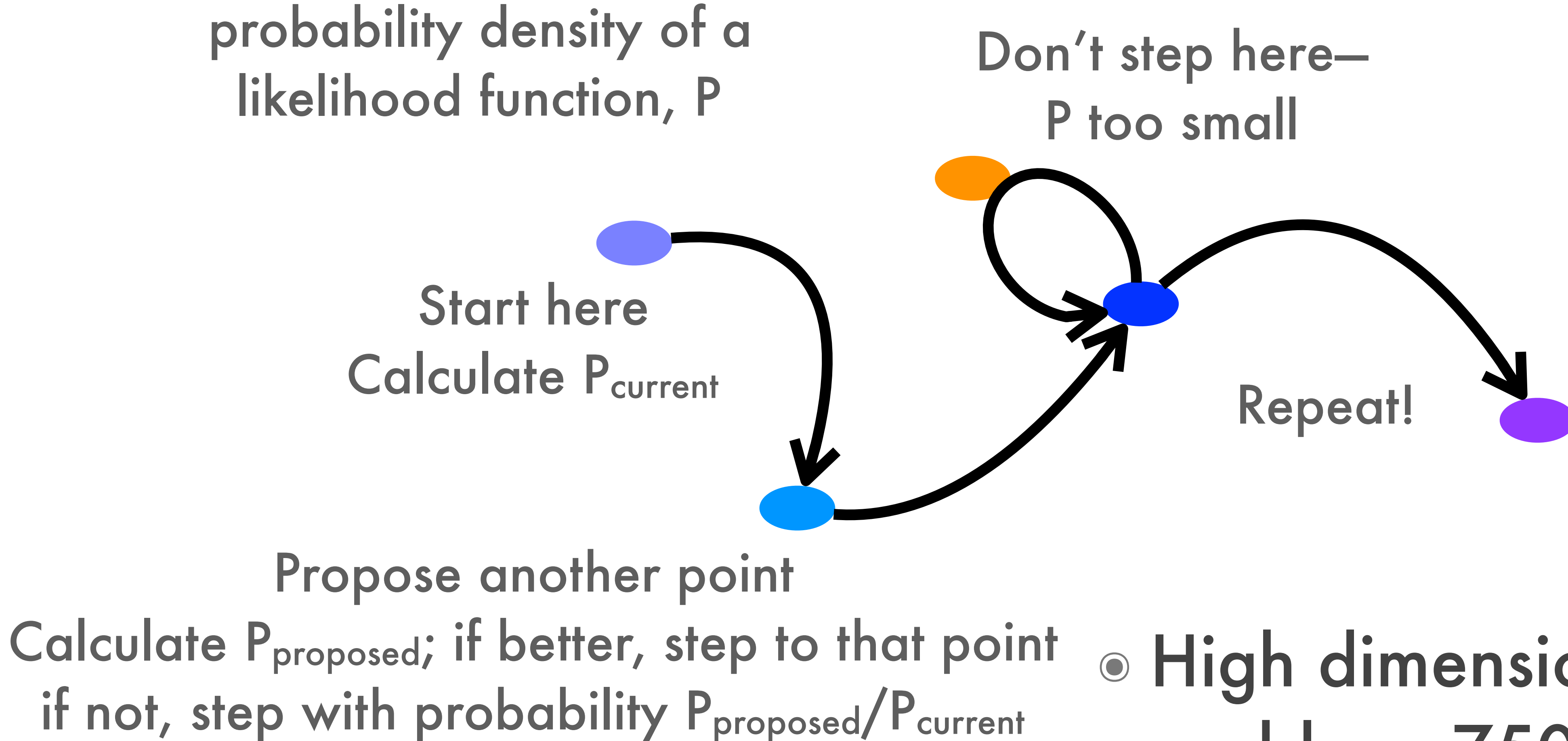
$$-\ln(P) = c + \sum_i^{ND280bins} N_i^p(\vec{b},\vec{x},\vec{d}) - N_i^d \ln N_i^p(\vec{b},\vec{x},\vec{d})$$
$$+ \sum_i^{N_\mu \text{ bins}} N_{\mu,i}^p(\vec{\theta},\vec{b},\vec{x},\vec{s}) - N_{\mu,i}^d \ln N_{\mu,i}^p(\vec{\theta},\vec{b},\vec{x},\vec{s})$$
$$+ \sum_i^{N_e \text{ bins}} N_{e,i}^p(\vec{\theta},\vec{b},\vec{x},\vec{s}) - N_{e,i}^d \ln N_{e,i}^p(\vec{\theta},\vec{b},\vec{x},\vec{s})$$
$$+ \tfrac{1}{2}\Delta\vec{b}^T V_b^{-1}\Delta\vec{b} + \tfrac{1}{2}\Delta\vec{x}^T V_x^{-1}\Delta\vec{x} + \tfrac{1}{2}\Delta\vec{d}^T V_d^{-1}\Delta\vec{d}$$
$$+ \tfrac{1}{2}\Delta\vec{s}^T V_s^{-1}\Delta\vec{s} + \tfrac{1}{2}\Delta\vec{\theta}_{sr}^T V_{\theta sr}^{-1}\Delta\vec{\theta}_{sr}$$

How well does the data agree with our prediction?

What prior understanding did we put into our prediction?

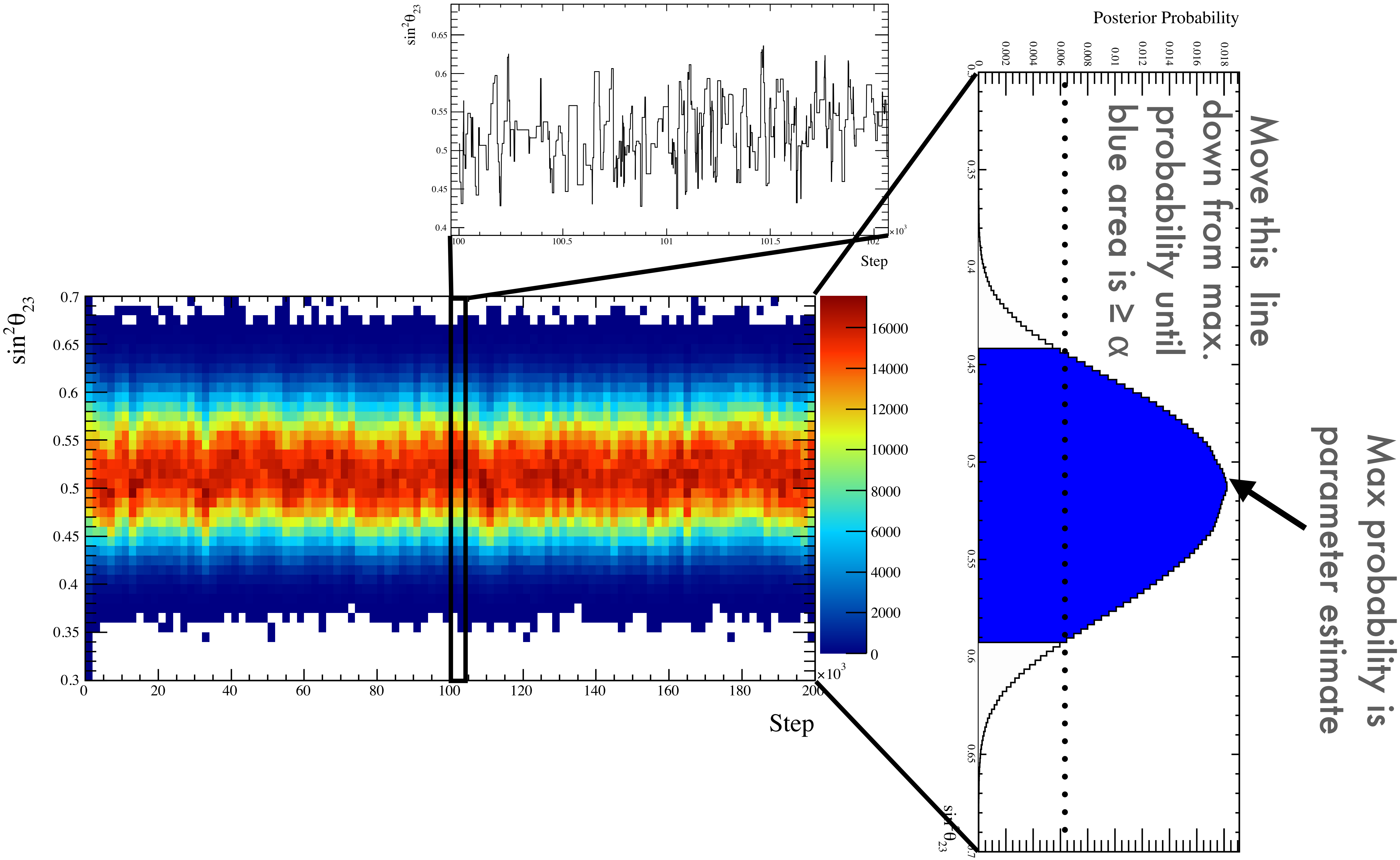
Markov Chain Monte Carlo and GPUs

A Markov Chain maps out the probability density of a likelihood function, P



- High dimensionality problem: 750 parameters
- Use Metropolis-Hastings algorithm with MCMC; doesn’t require calculating likelihood derivatives

Estimating Parameters and Uncertainties



Current Cross Section Model

- Try to use fundamental parameters of the models
- Simulation is NEUT (numbers)
- Twenty-six parameters
  - Five for 1p1h
  - Three for 2p2h
  - Three for 1π (CC and NC)
  - Six FSI
  - Nine for CC Coherent, CC DIS, NC

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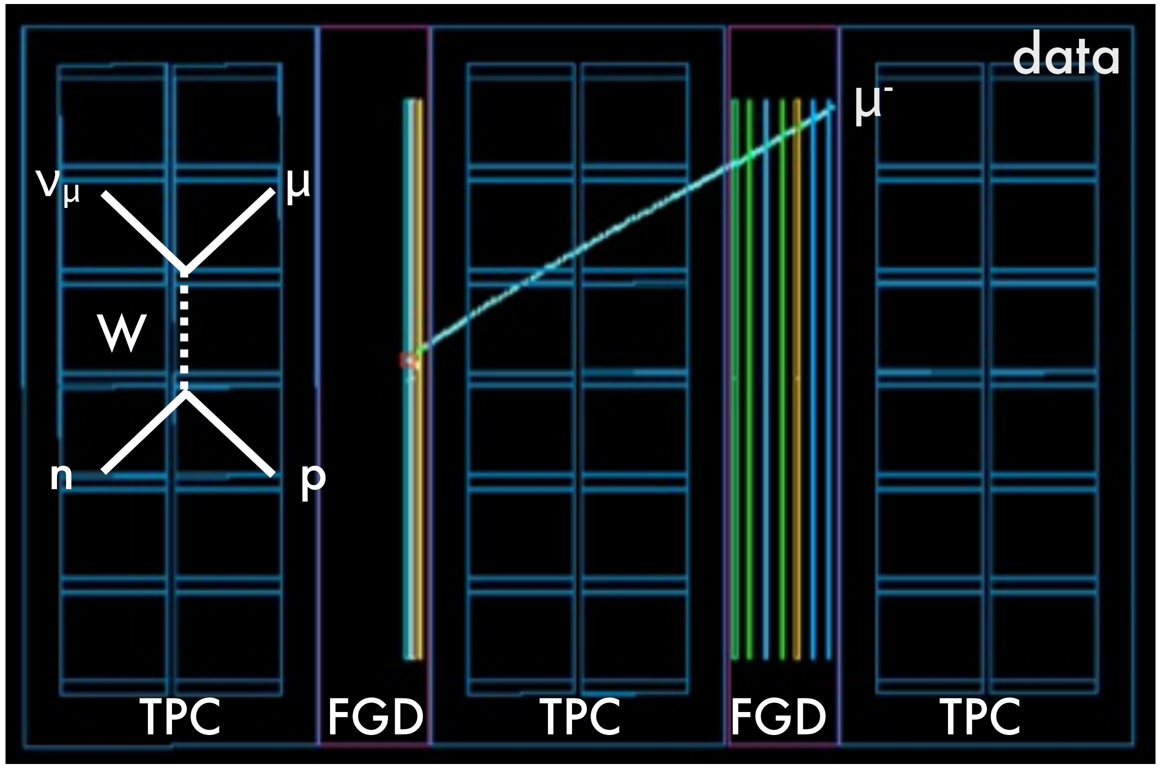
Focus on 1p1h

- M_A^{QE} is the only nucleon level parameter
- Assume a RFG nuclear model
  - Separate pF and Eb parameters for carbon and oxygen
- Apply fixed RPA correction
- Binned $p_\mu - \cos\theta_\mu$ '1p1h' uncertainty coming from different models
- *For 2017*: include uncertainties for RPA

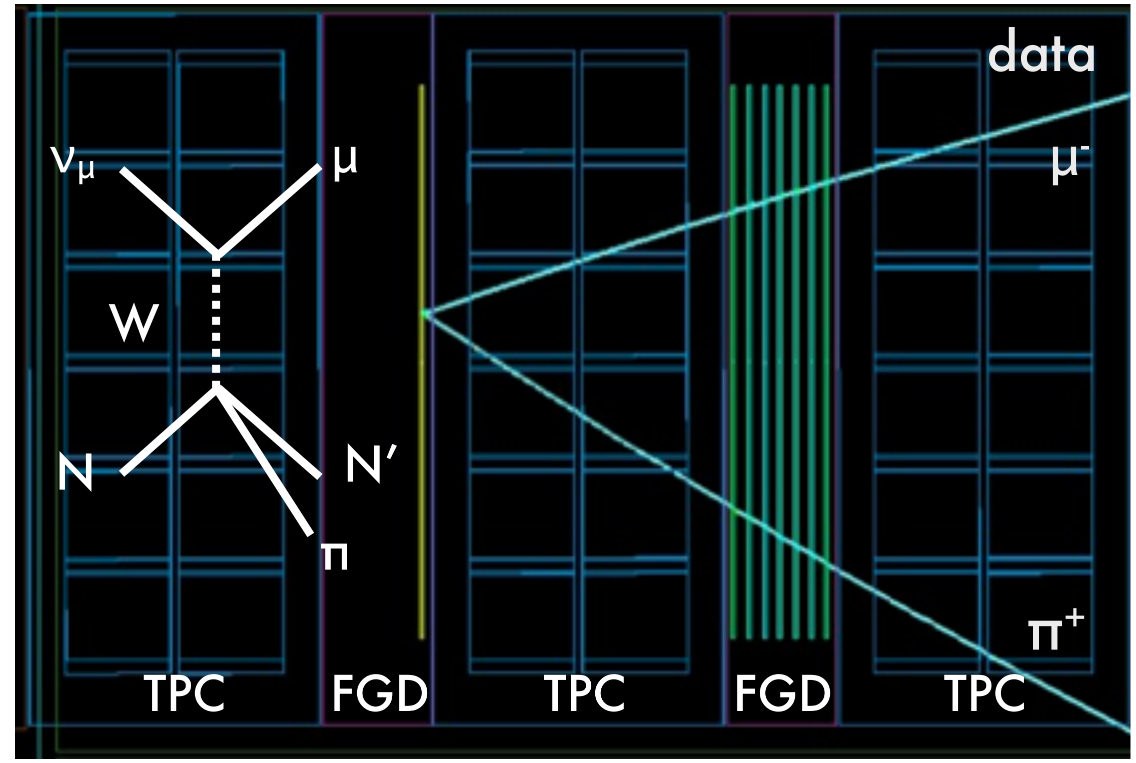
Focus on 2p2h

- Use 'Nieves' 2p2h model
- Normalization parameter for carbon and oxygen separately
- Relative uncertainty for $\bar{\nu}$ vs ν
- For 2017:
  - Add 'shape' parameter to allow slosh between π-less-Δ-like and non-π-less-Δ-like

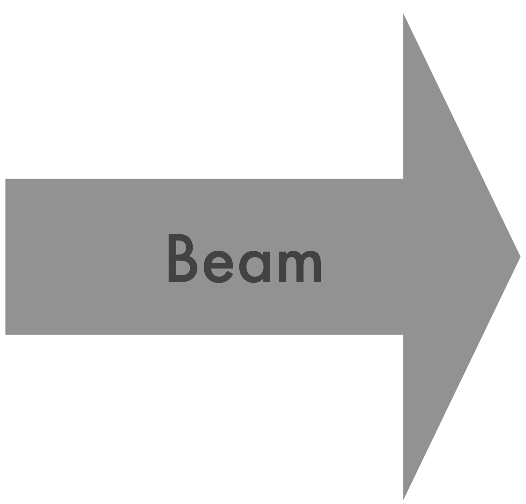
CC0π

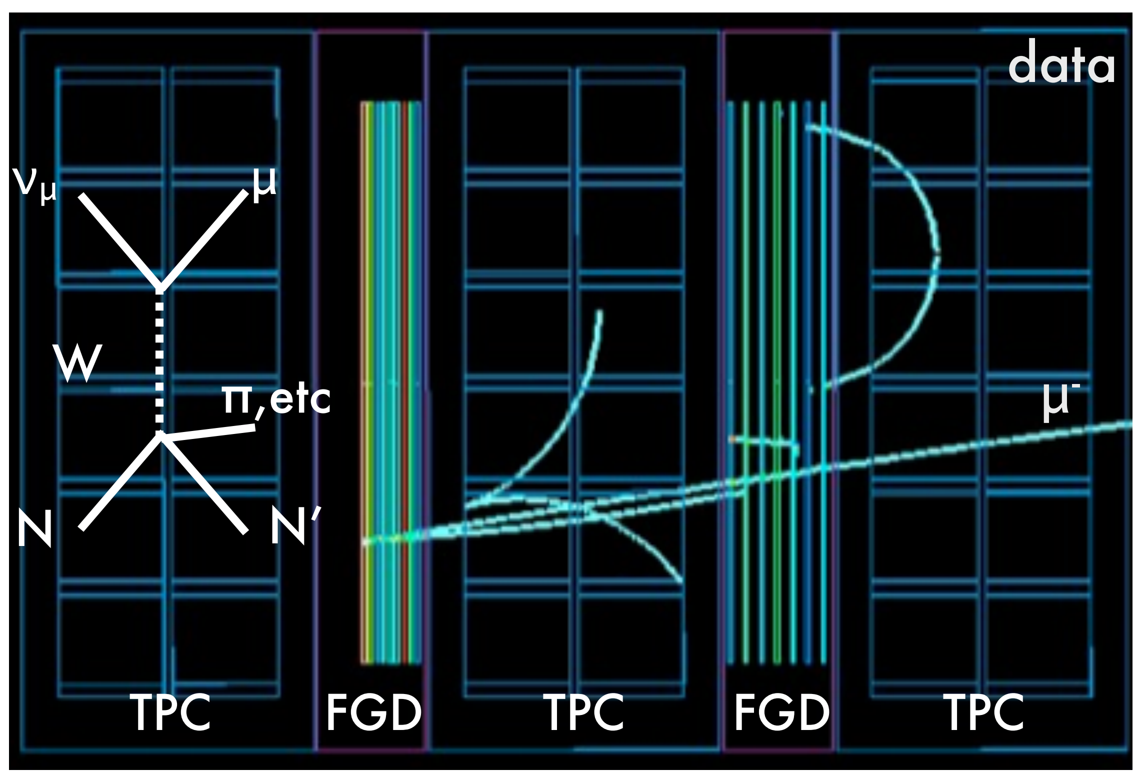


CC1π^+



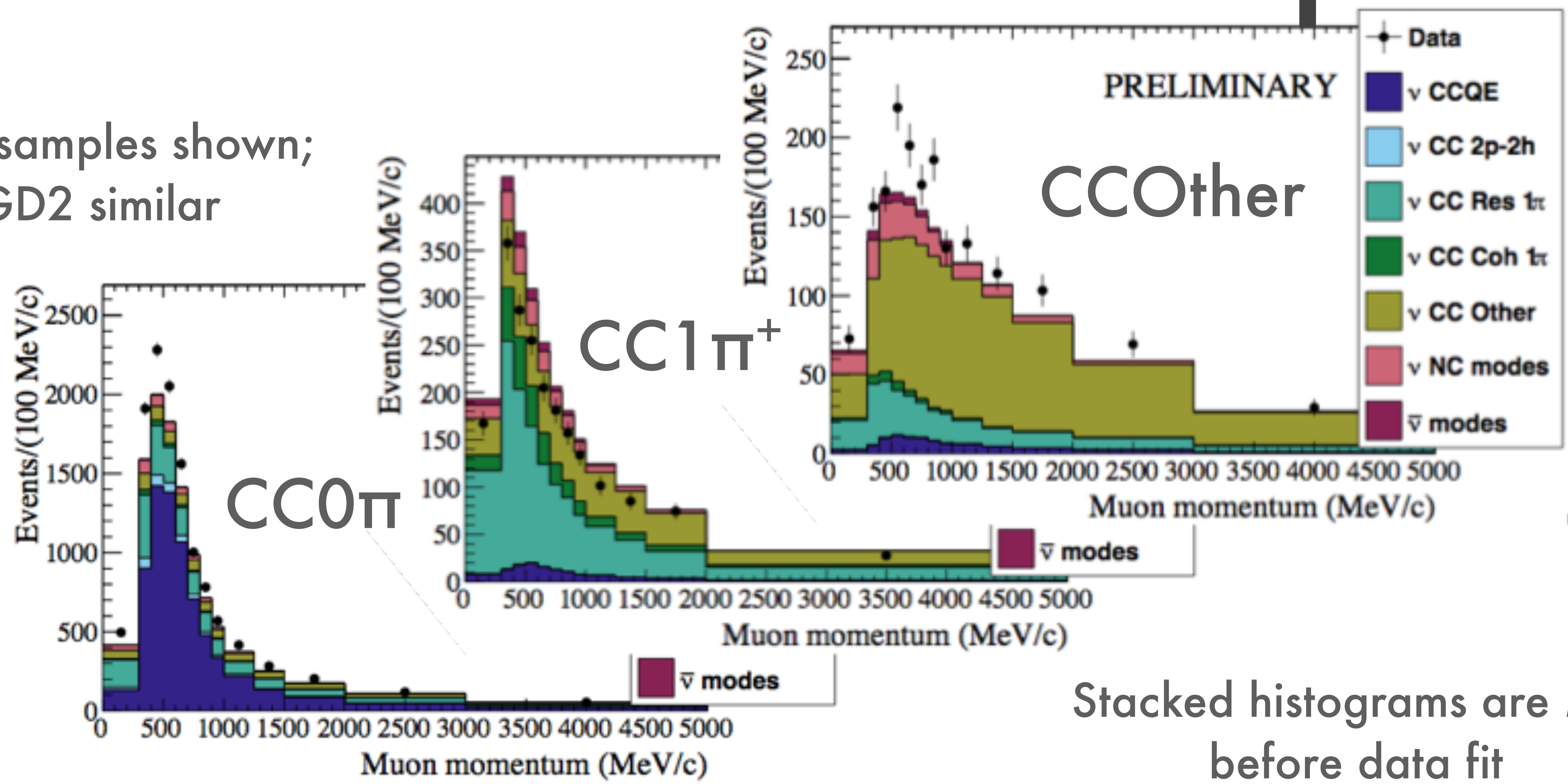
CC other





ND280 ν-mode samples

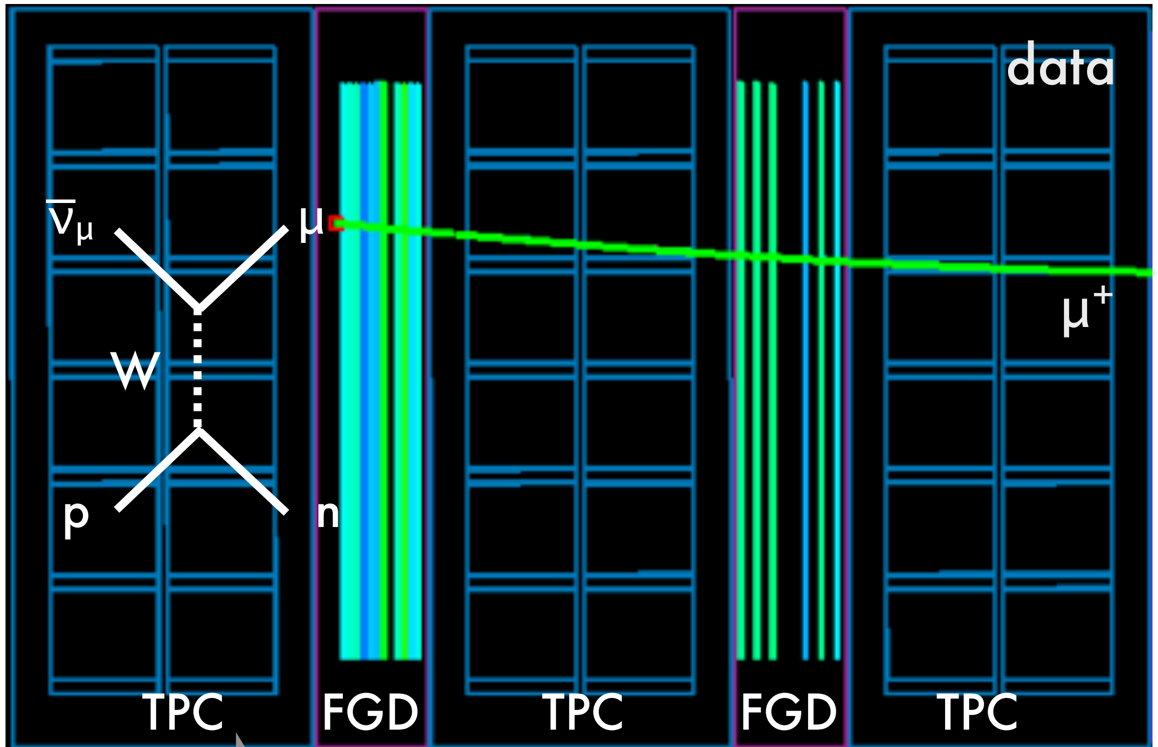
FGD1 samples shown;
FGD2 similar



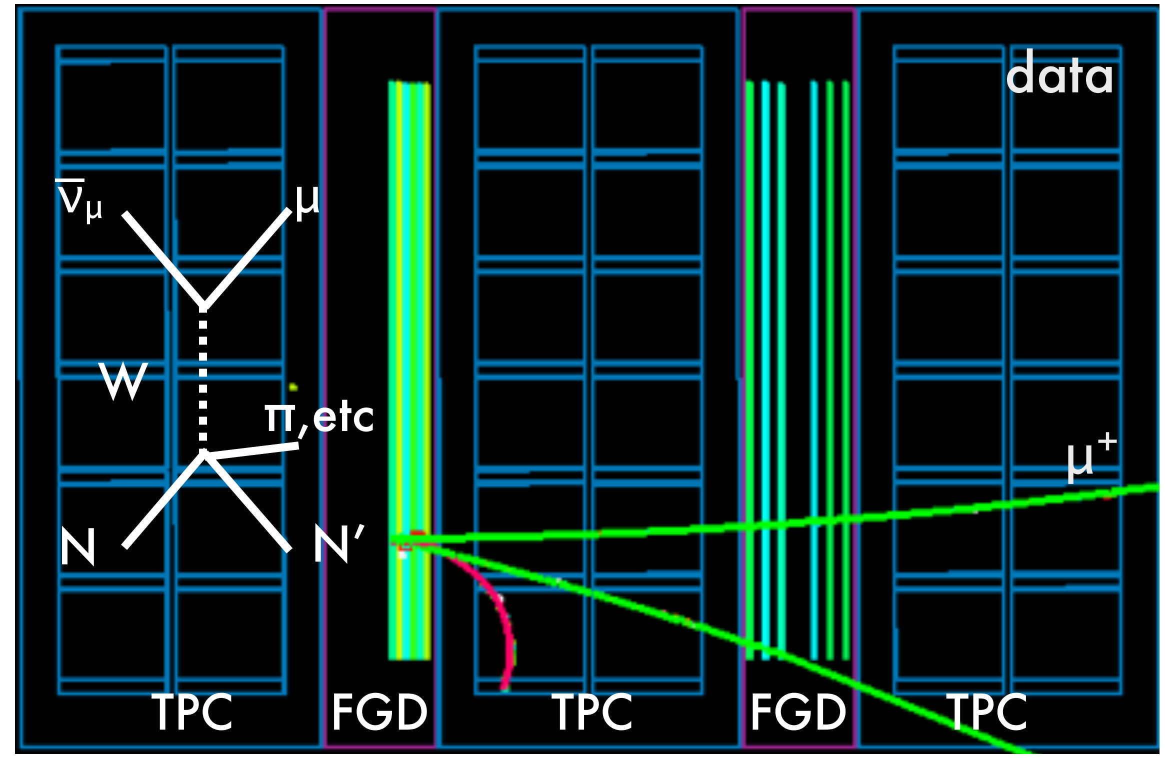
Stacked histograms are MC
before data fit

- Three samples allow sensitivity to different beam energies and cross section interaction modes
- High statistics in neutrino mode provide strong constraints
- CC0π and CC Other samples are underestimated by model; CC1π+ is overestimated

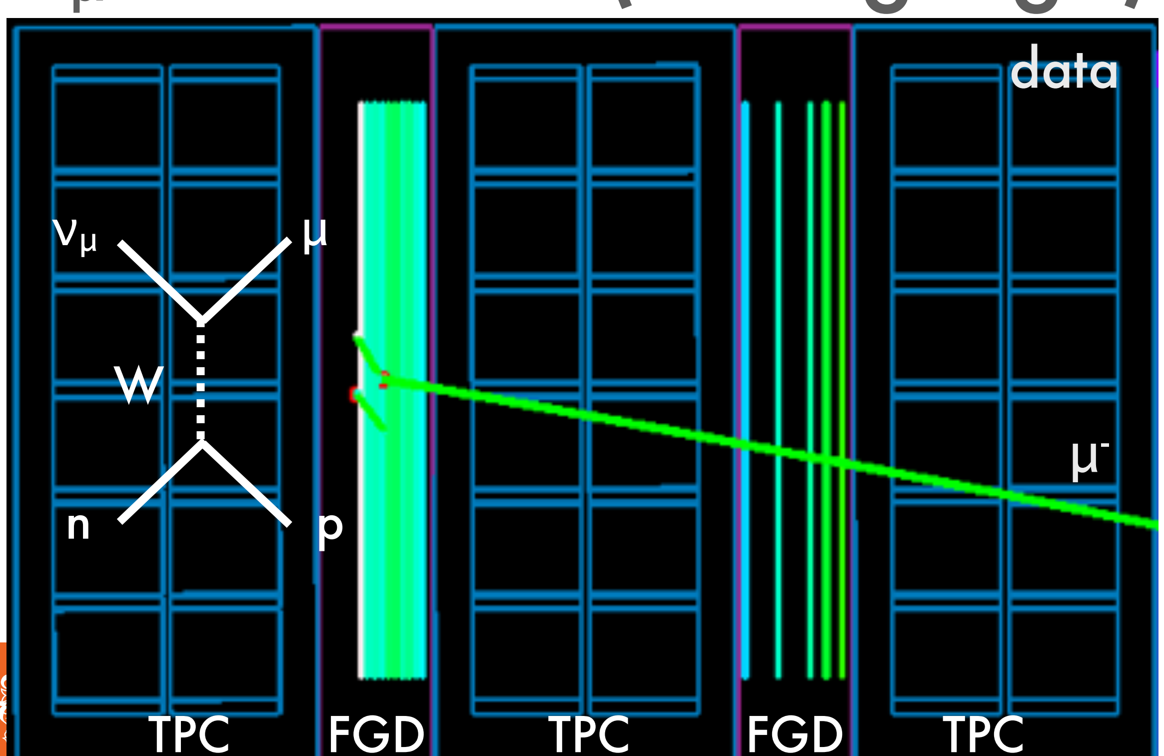
$\bar{\nu}_\mu$ CC-1Track



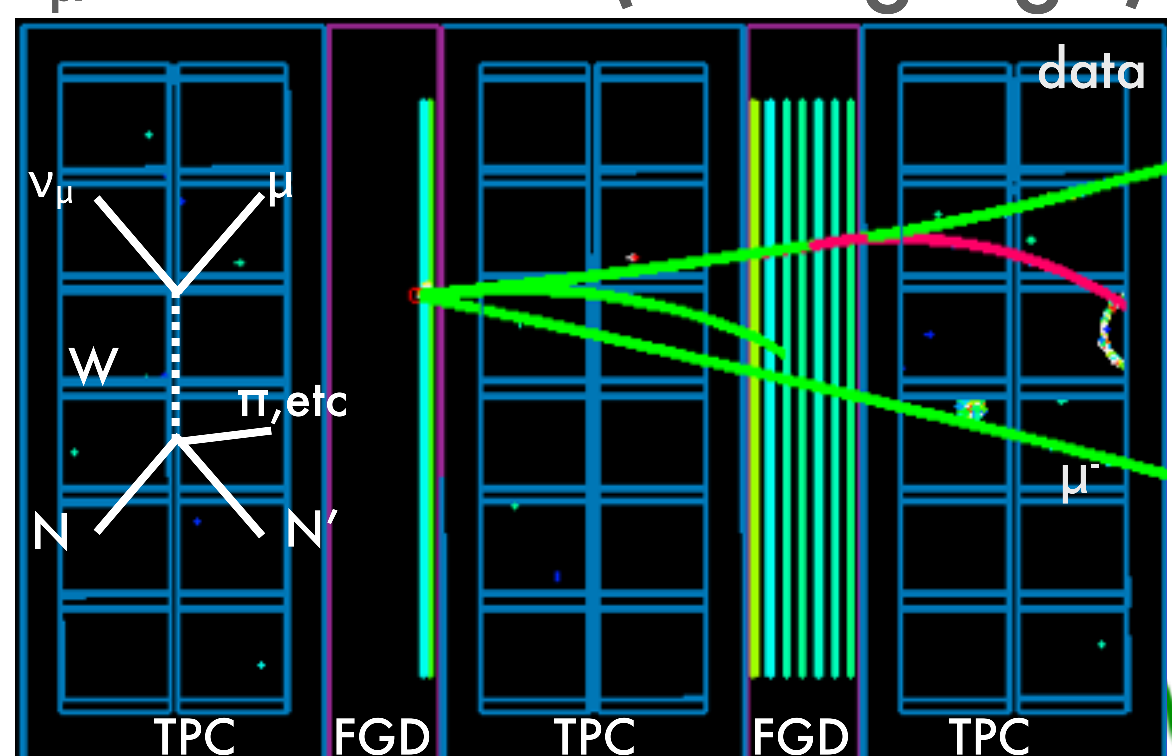
$\bar{\nu}_\mu$ CC-NTrack



ν_μ CC-1Track (wrong sign)

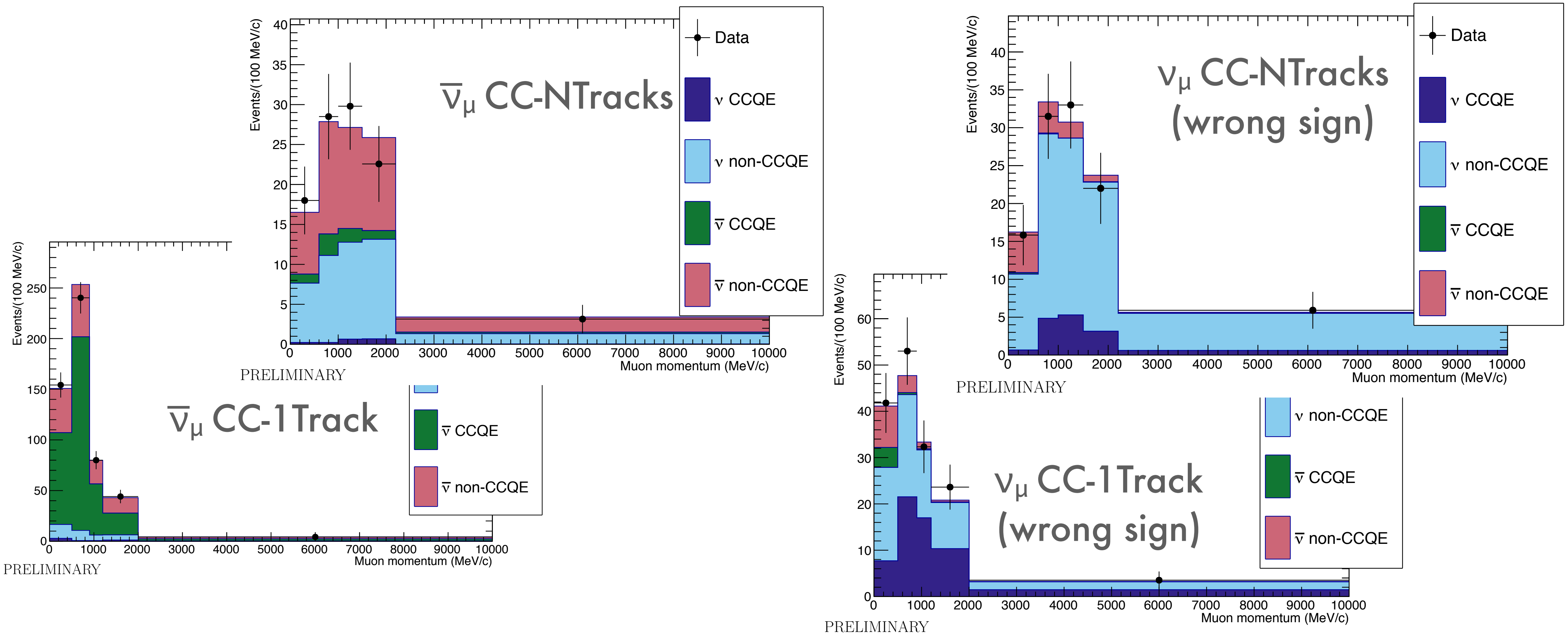


ν_μ CC-NTrack (wrong sign)



ND280 $\bar{\nu}$-mode Samples

Stacked histograms are MC before data fit

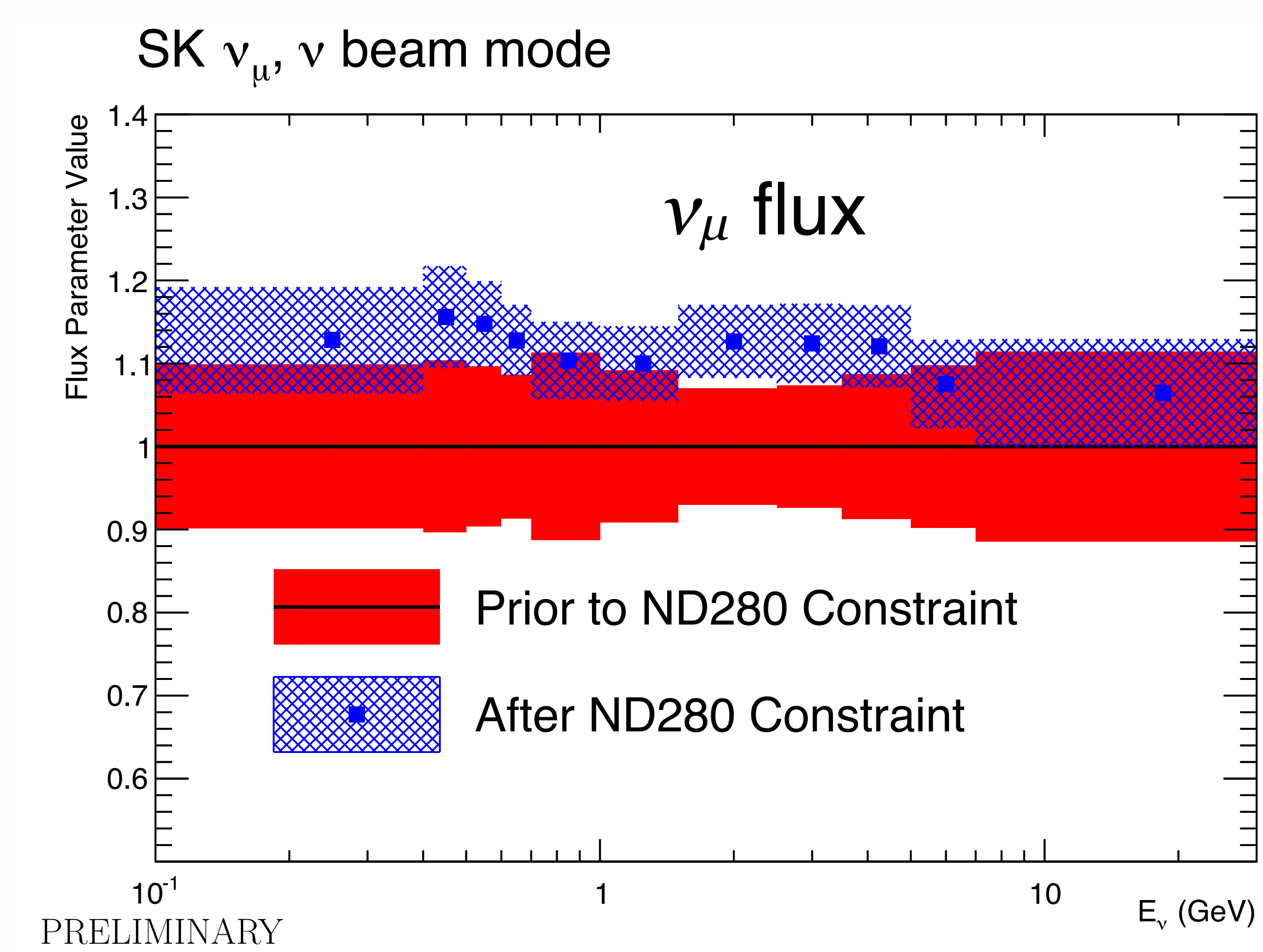


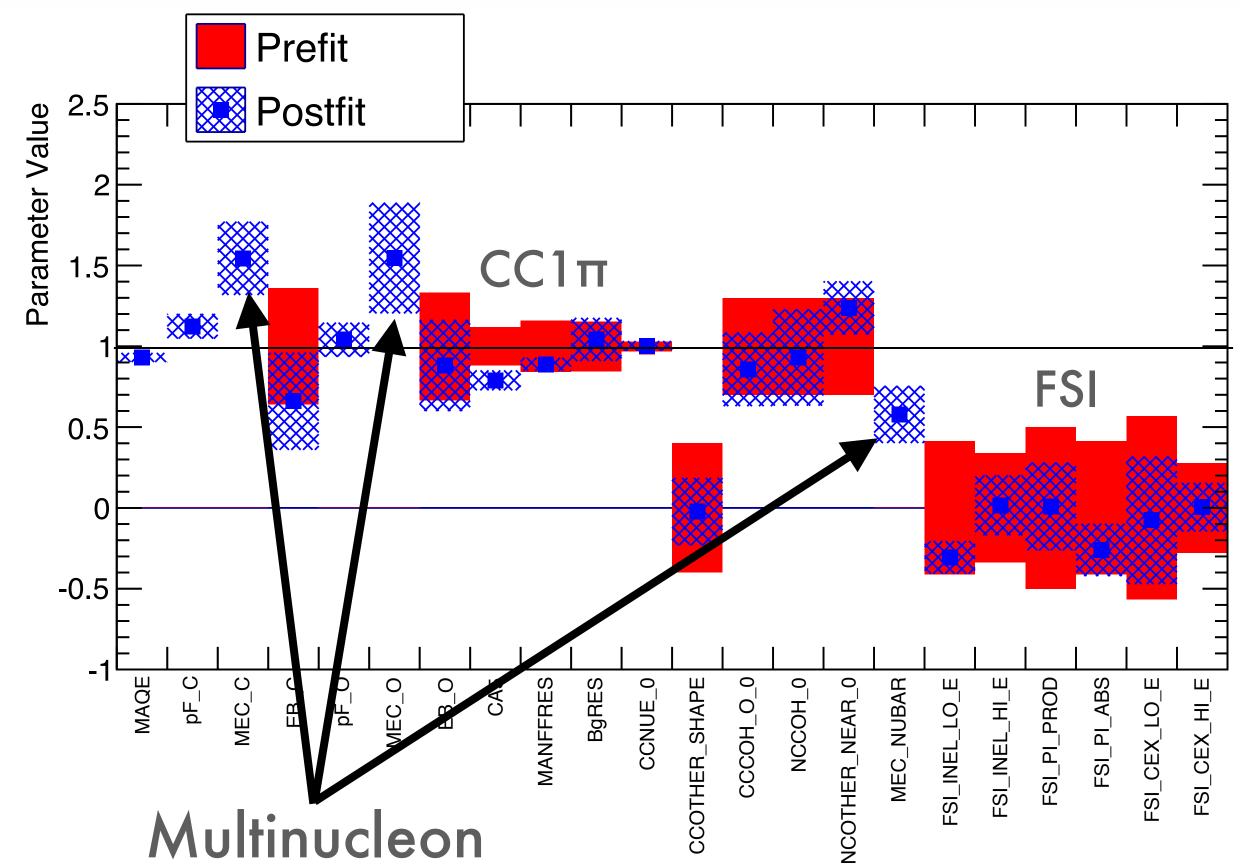
- Samples are still statistically small compared to ν-mode

Near Detector Results

2016

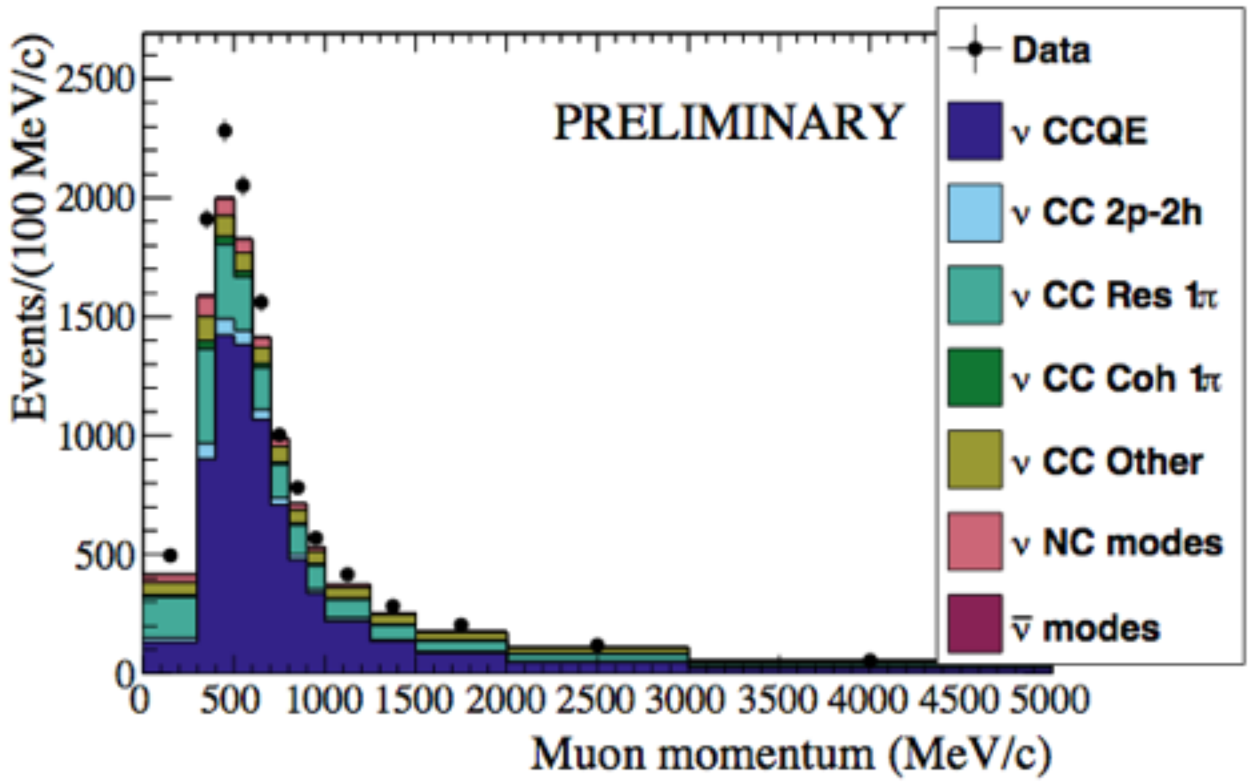
- Flux parameters are generally increased
- Some cross section parameters—especially the carbon multinucleon parameter—are changed significantly from prior values



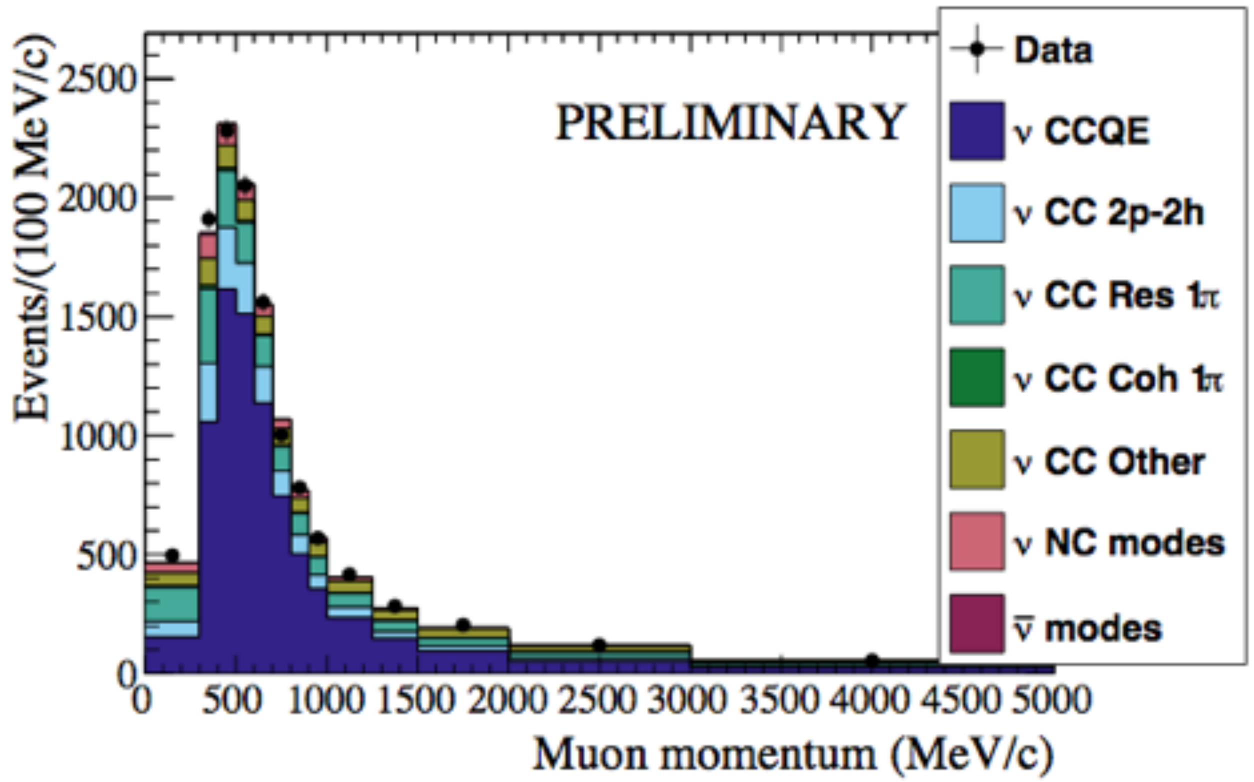


CC0π Samples

Before analysis



After analysis



- Clear that data is in better agreement after the analysis
- Multinucleon component of distribution is noticeably increased

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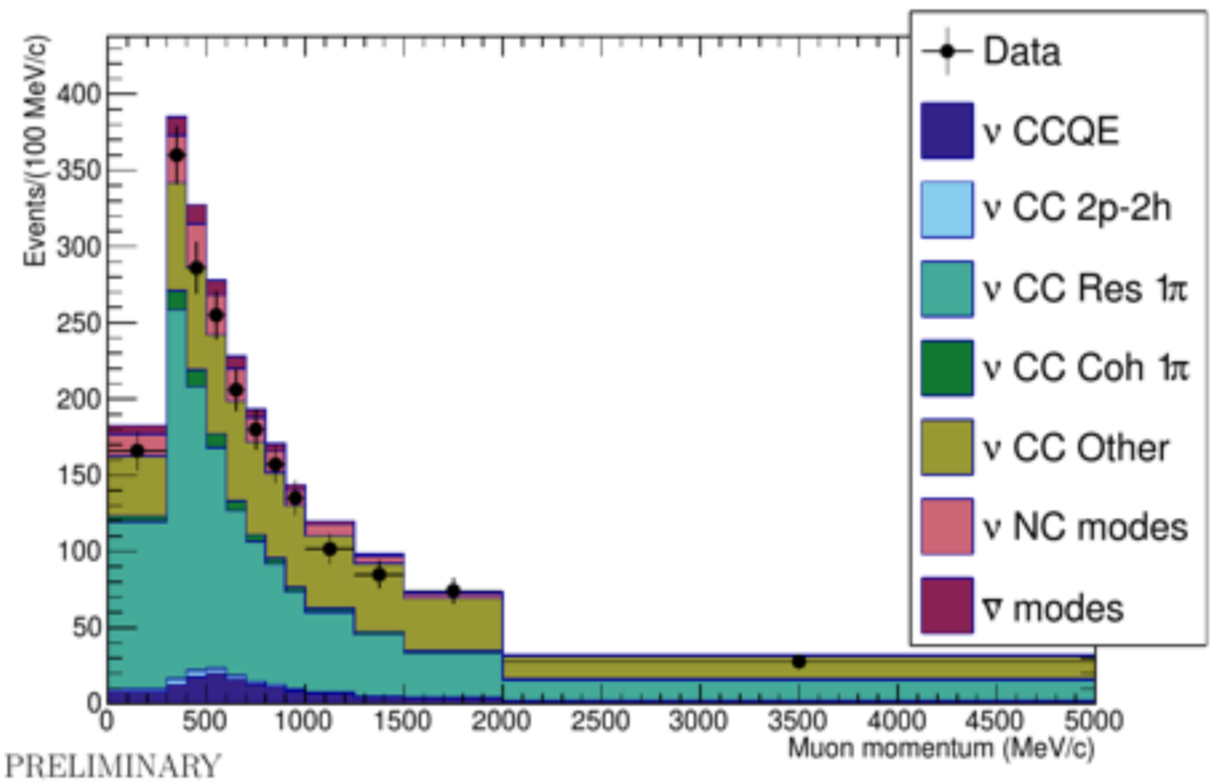
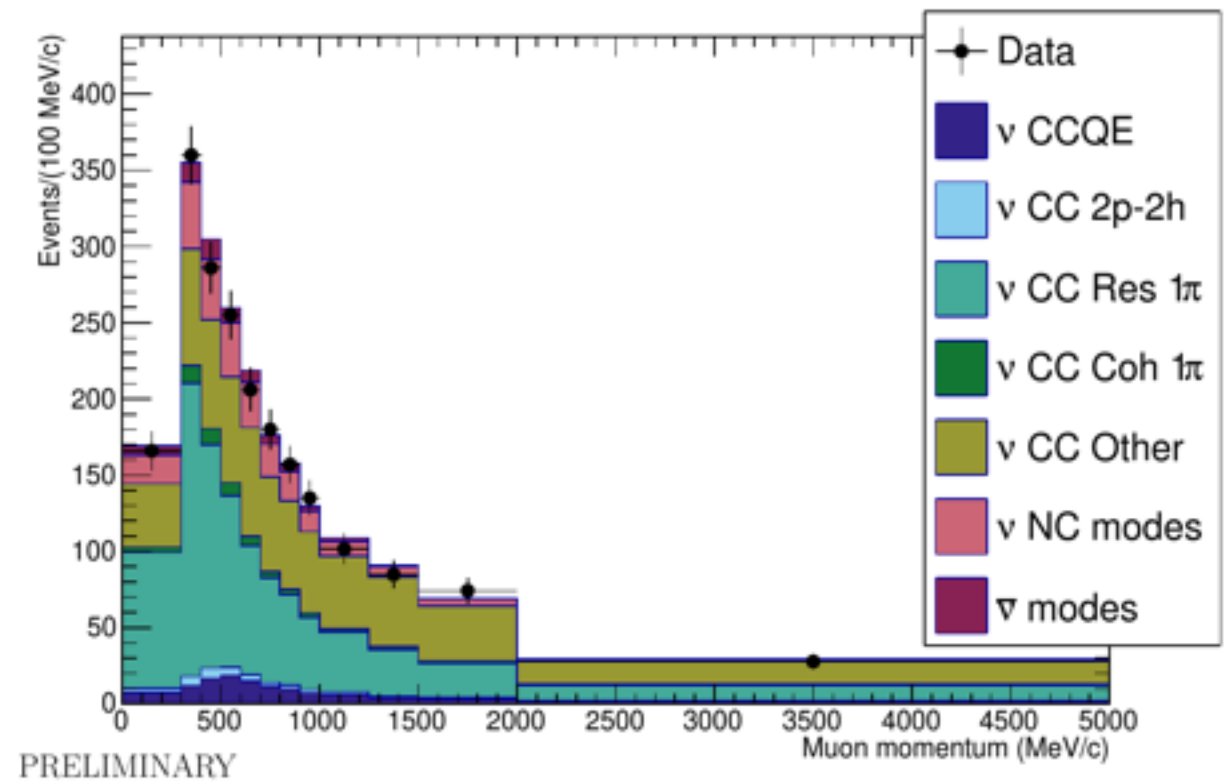
CC1π Samples

Before analysis



After analysis



- CC Res 1π component is reduced in both absolute and relative terms as part of the CC1π sample

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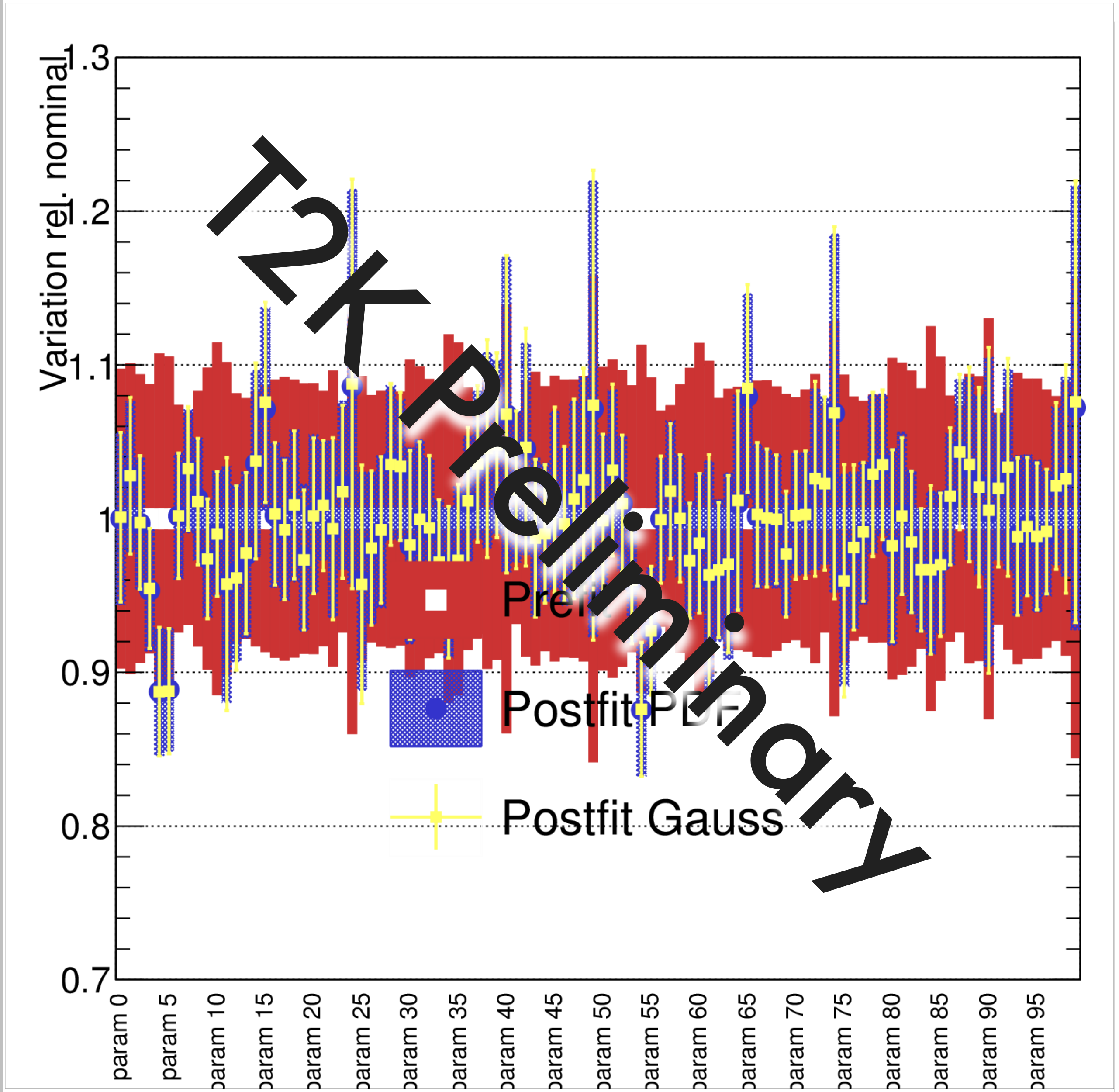
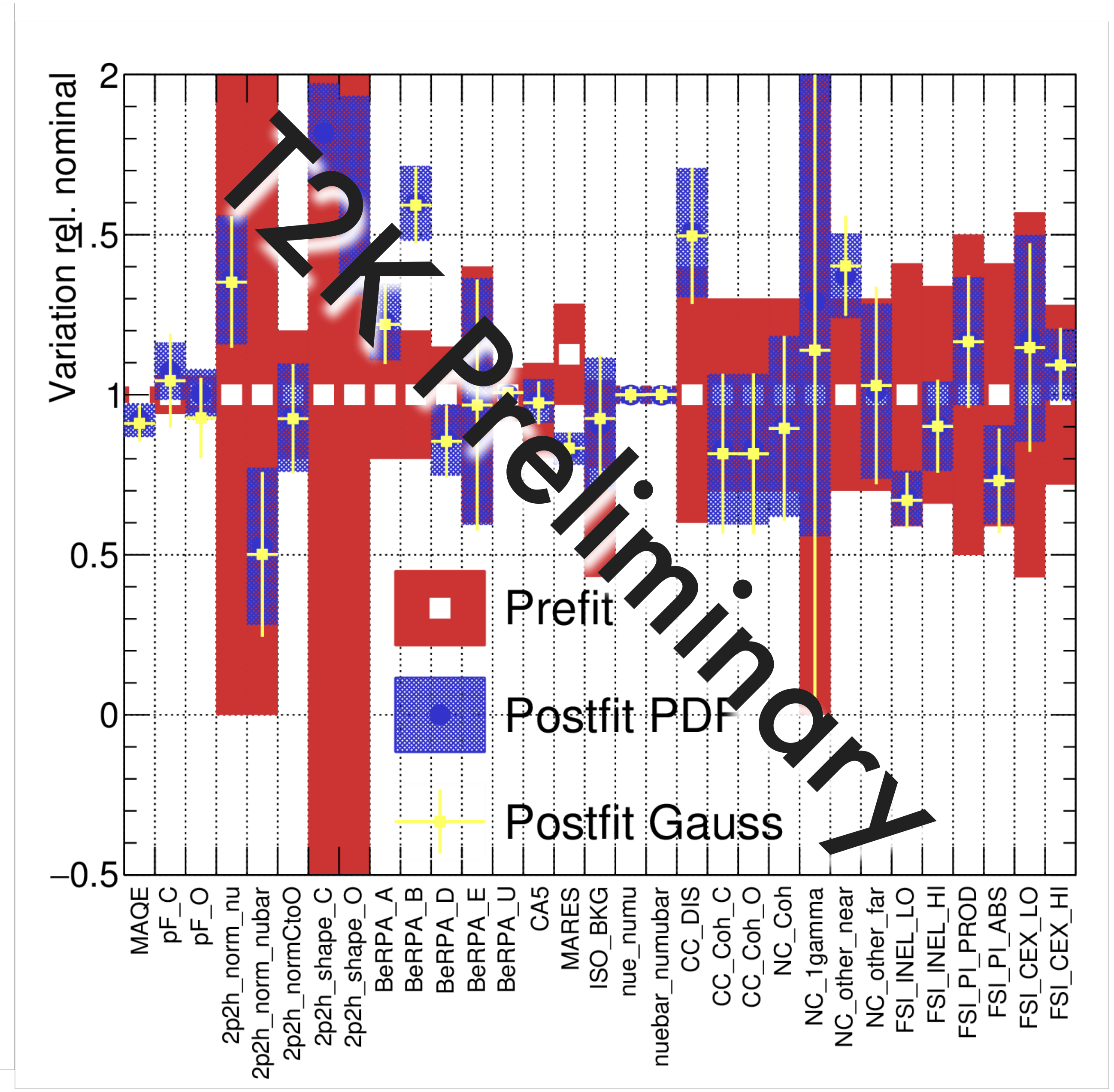
Near Detector Results

2017





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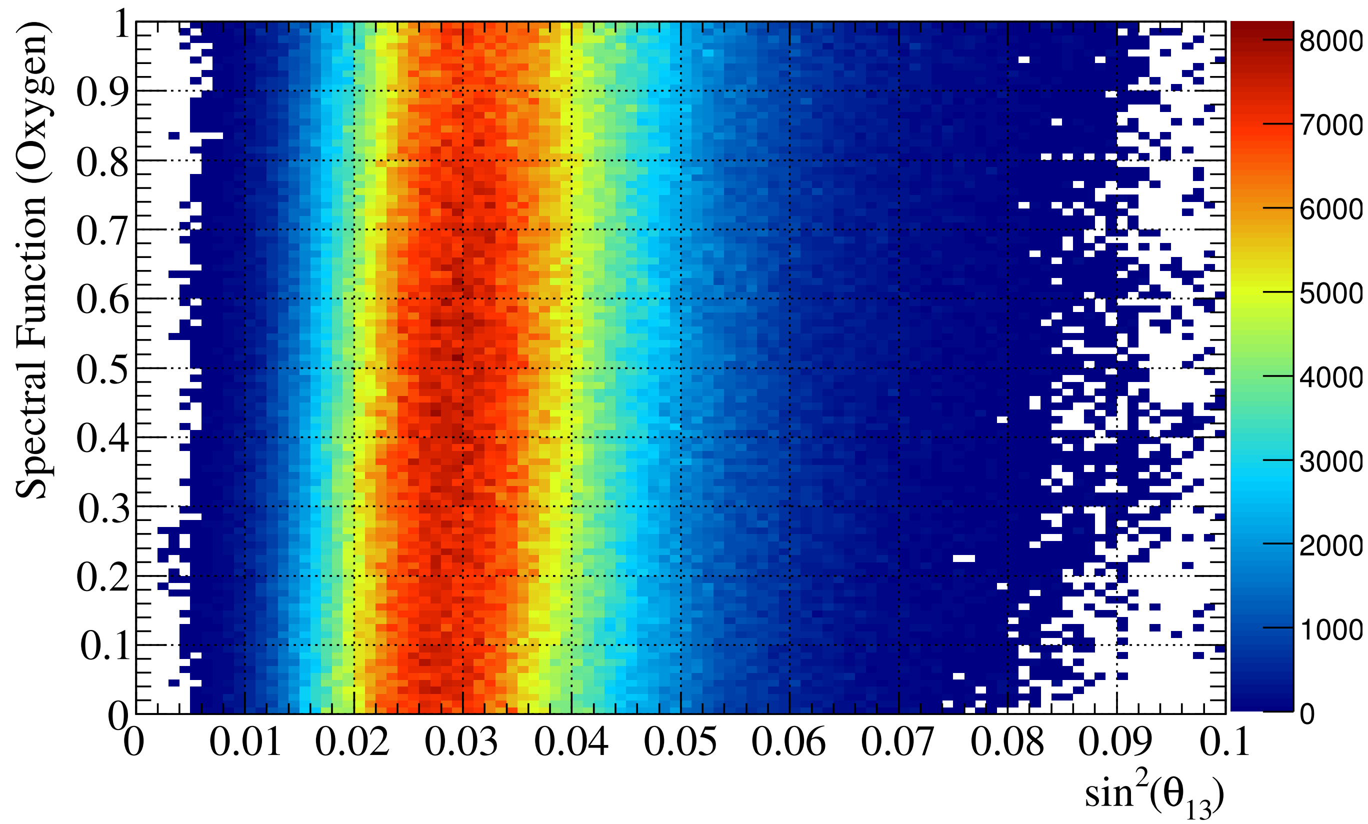
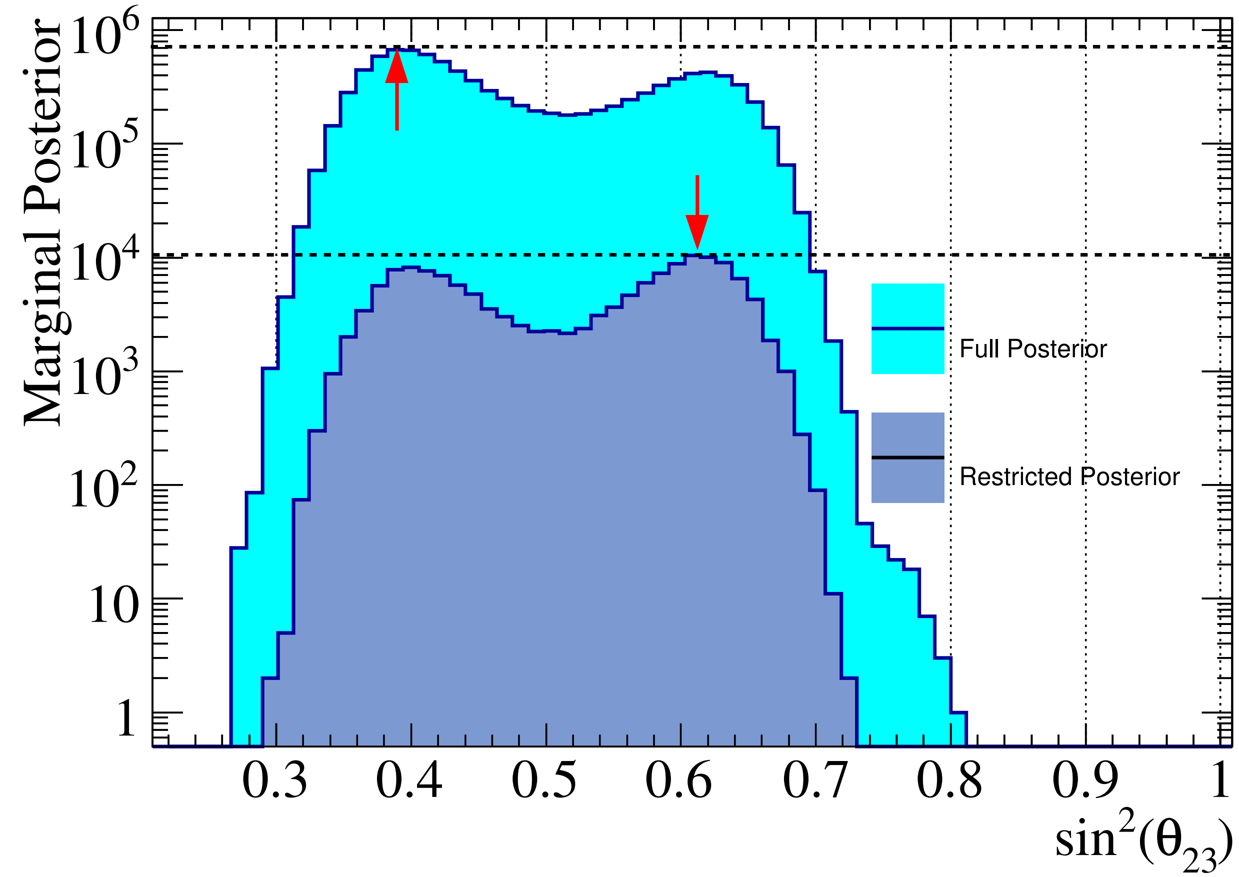
Two Models?

- Big question: why not include alternate nuclear models?
- We tried this, several analyses ago!
- Gave up on this because what does 0.25 spectral functions mean?



Marginalization

- There are (at least) two ways to eliminate systematic parameters from your analysis: marginalization and profiling
- On T2K, we have found that cross section parameters, because they can be significantly non-gaussian, are a notable source of difference between the methods

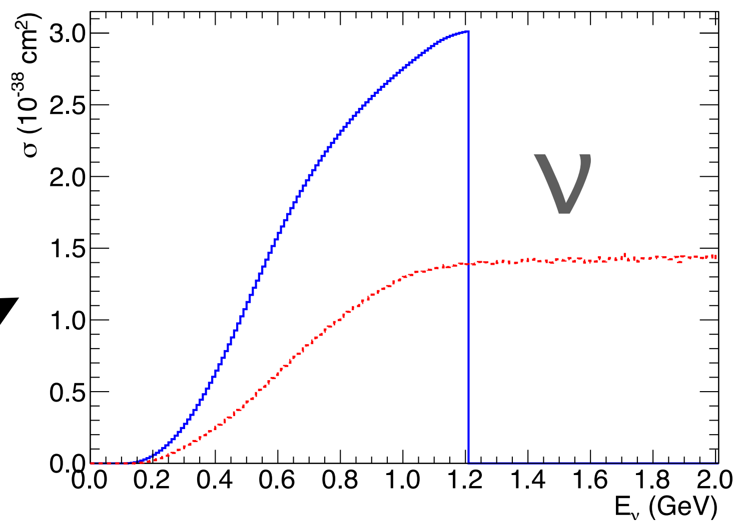


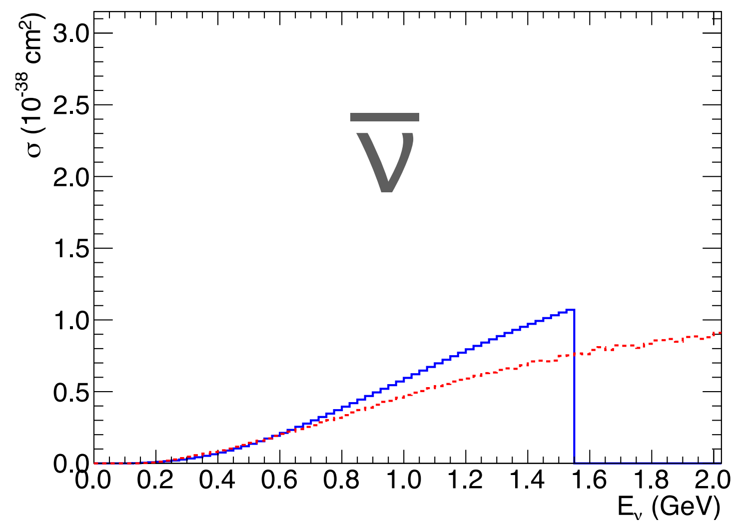
Fake Data Sets

- Take set of model changes
- Make fake data without statistical error for both ND and SK
- Fit with the ‘default’ model
- Adjust model, if necessary

Model Choices

- Spectral function model for 1p1h
- Martini 2p2h model
- Nieves 1p1h model
- 2p2h shape
- RPA uncertainties





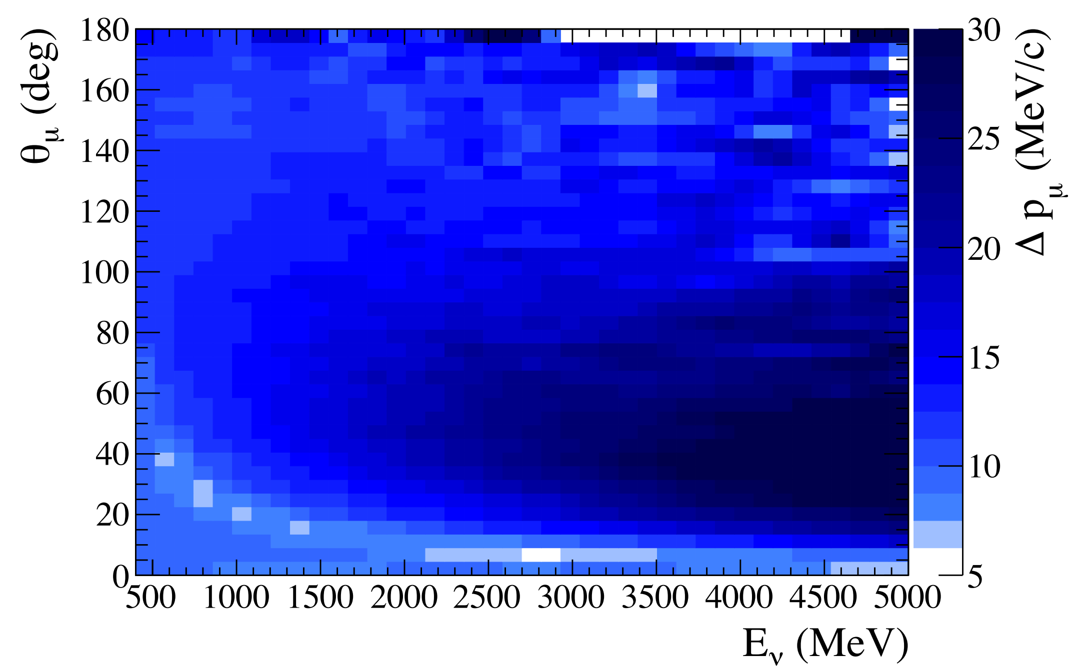


Figure of Merit

$$\text{Bias 1} = \frac{fit_{\text{Fake data}} - fit_{\text{Asimov}}}{\sigma_{\text{Asimov 1}}}$$

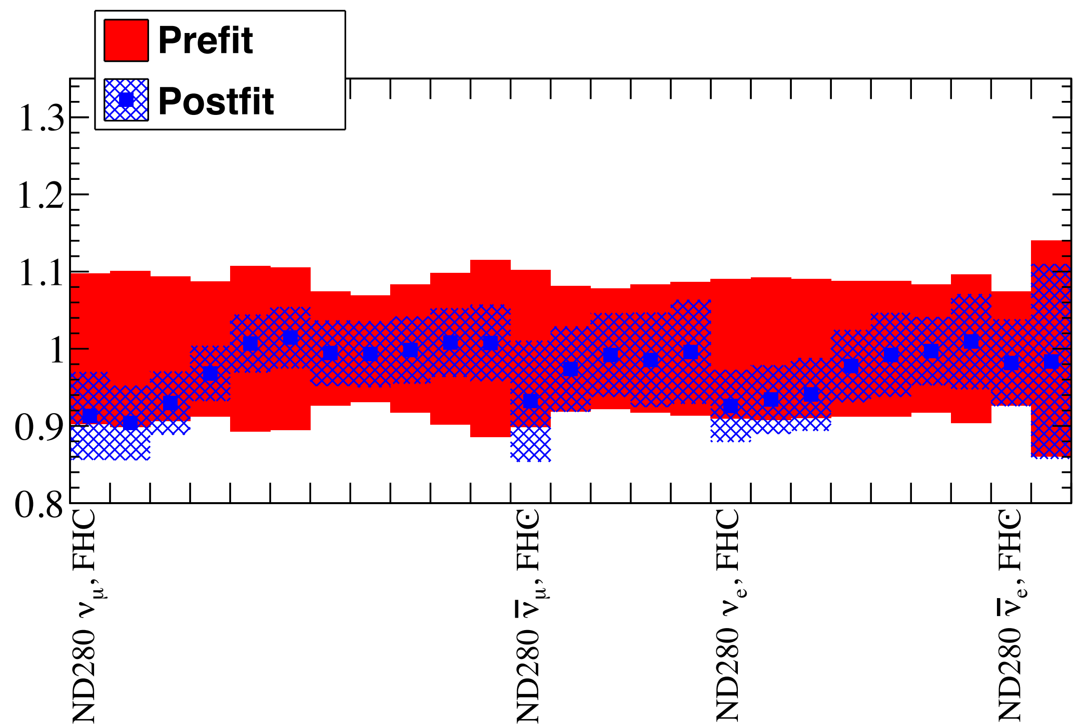
With current T2K statistics

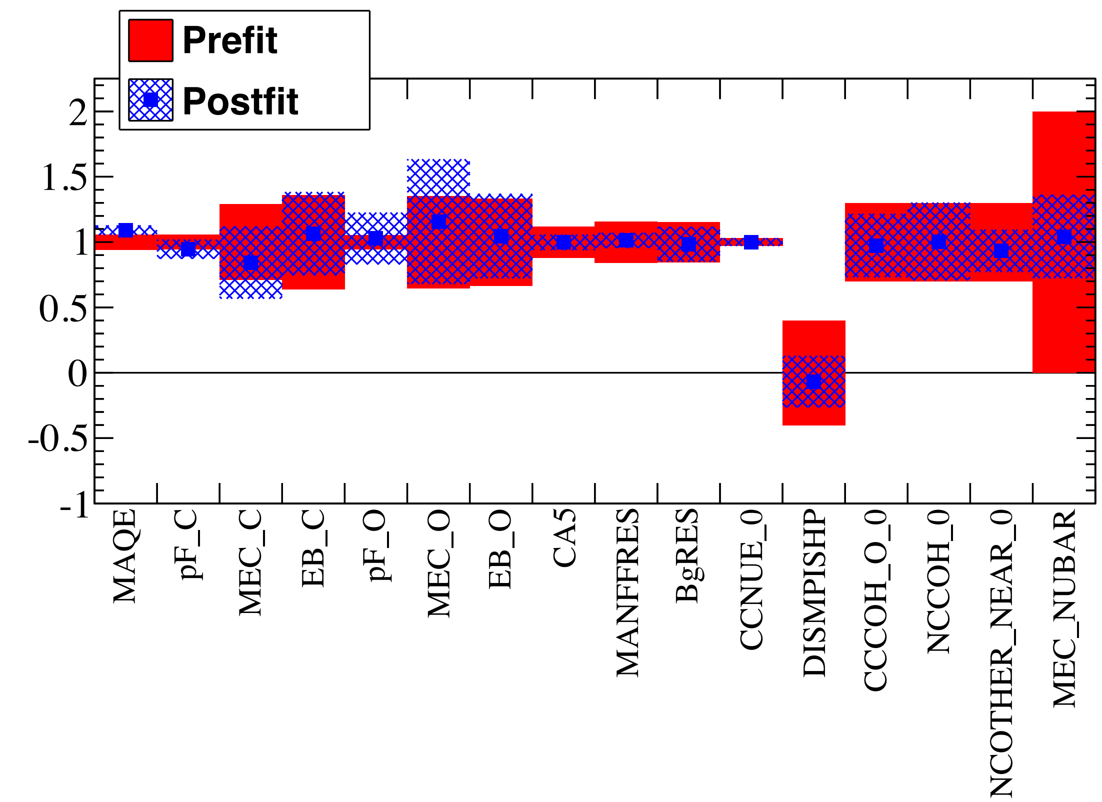
$$\text{Bias 2} = \frac{fit_{\text{Fake data}} - fit_{\text{Asimov}}}{\sigma_{\text{Asimov 2}}}$$

With full T2K statistics

Choose several sets of oscillation parameters, including non-maximal θ_{23} and $\delta_{CP} = 0, -\pi/2$

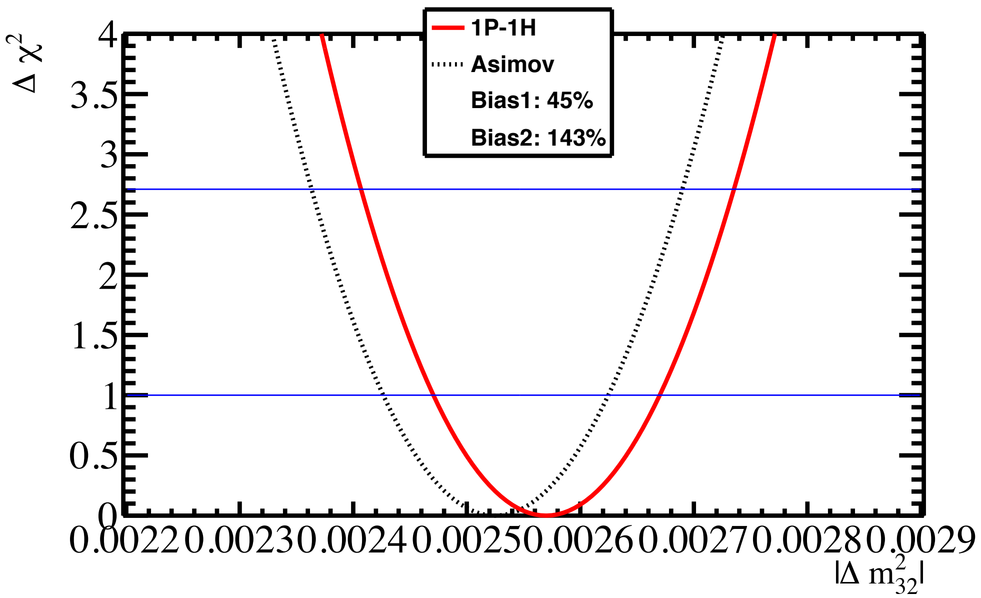
Differences in 1p1h model



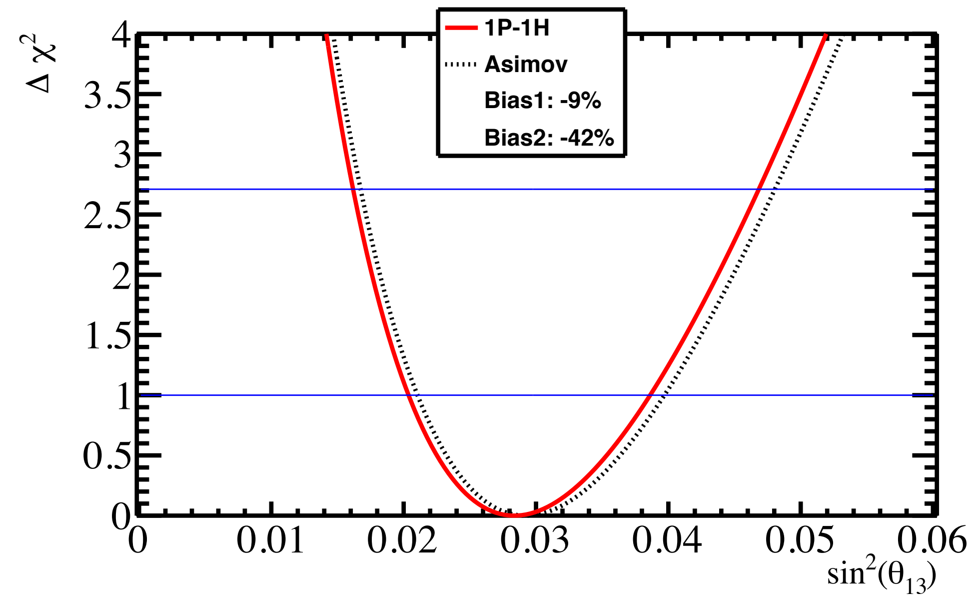


Flux generally pushed down; no large changes in cross section parameters

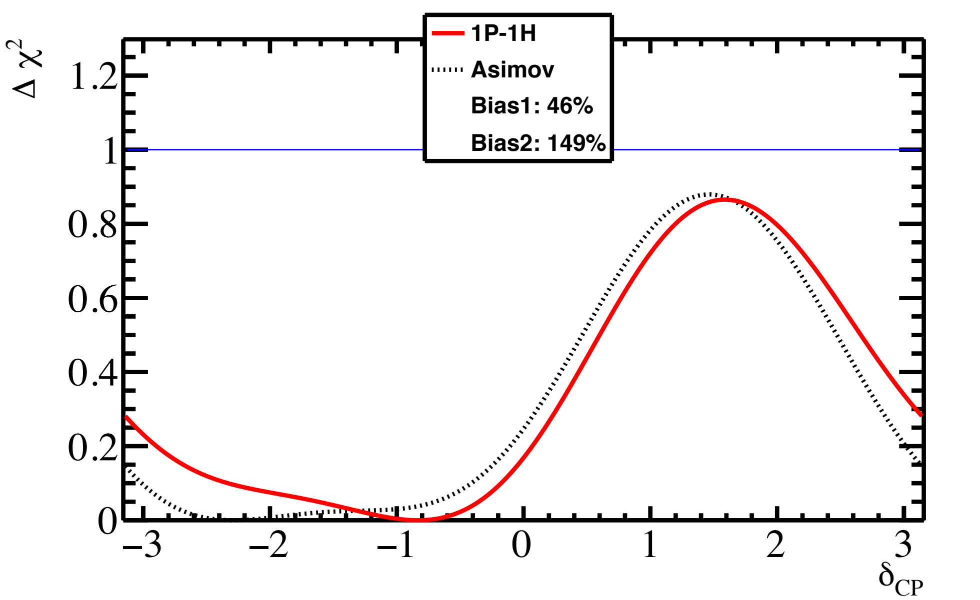
Differences in 1p1h model



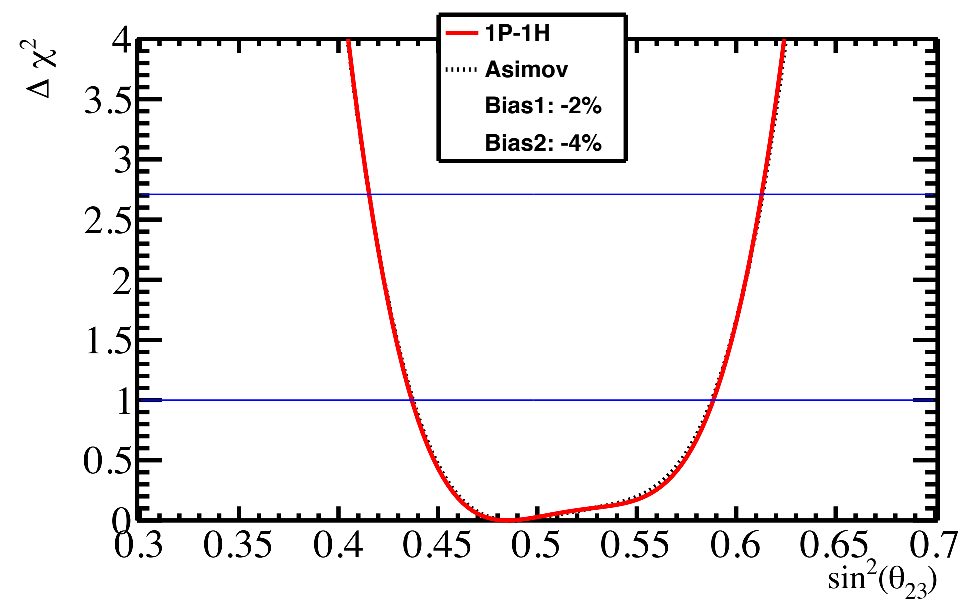
(a) $|\Delta m^2_{32}|$



(b) $sin^2(\theta_{13})$



(c) δ_{cp}



(d) $sin^2(\theta_{23})$

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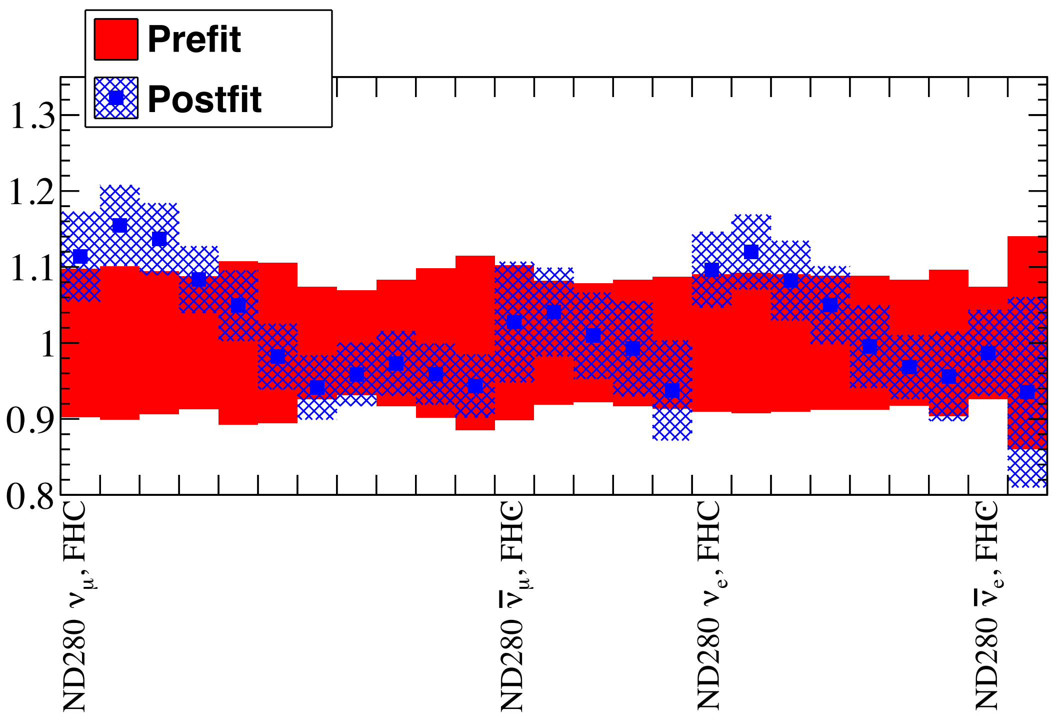
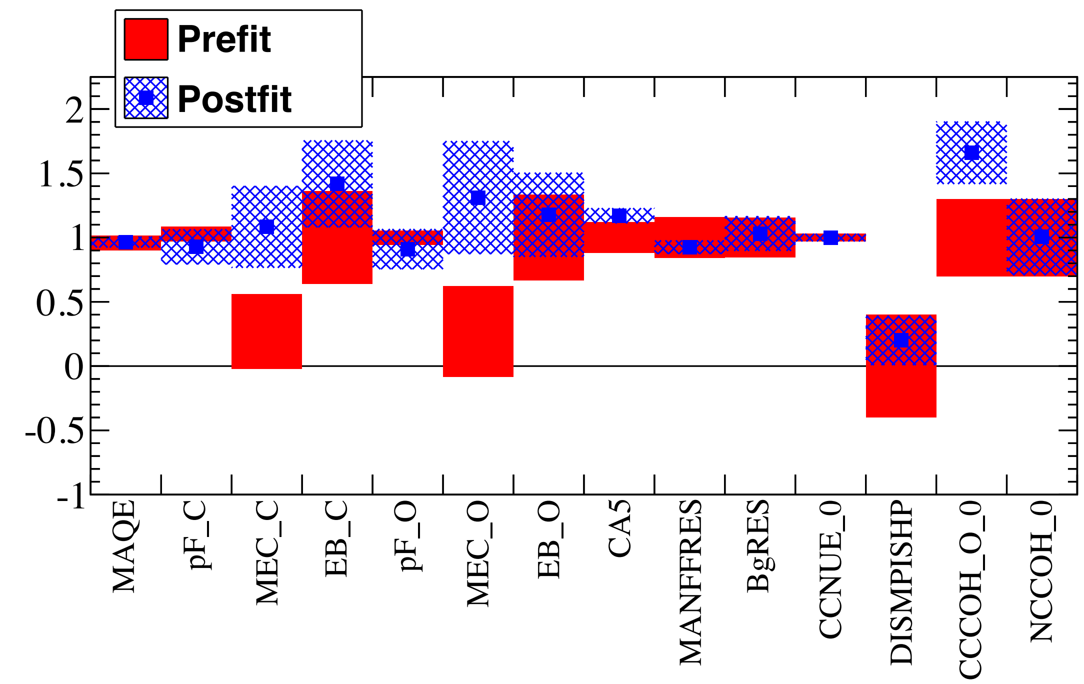
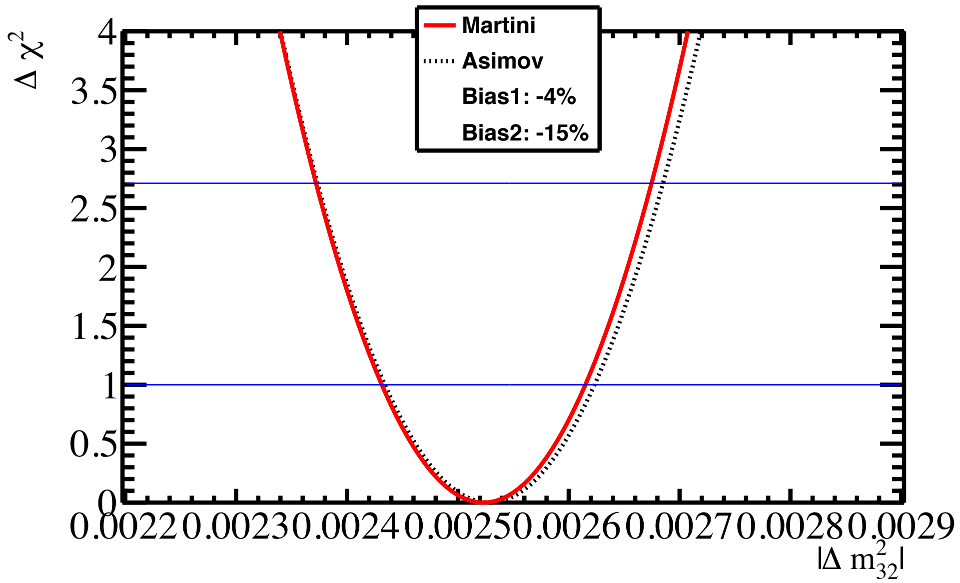
Martini 2p2h



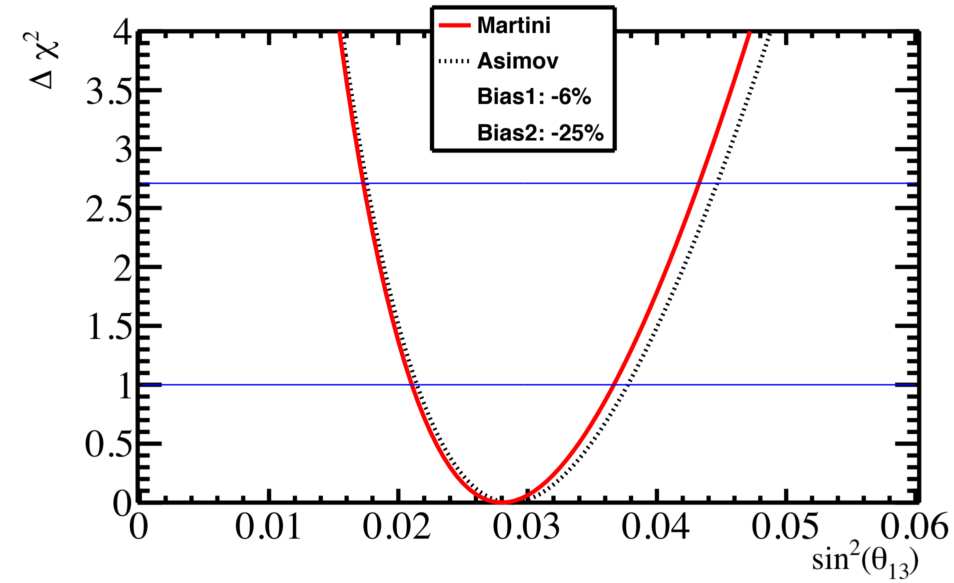


Something wacky happens to flux; no huge changes in cross section parameters

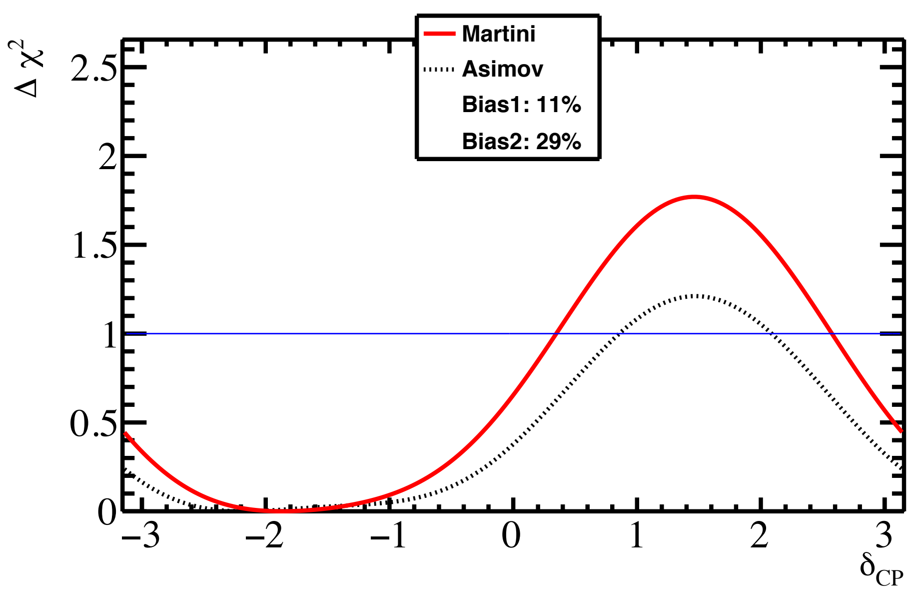
Martini 2p2h



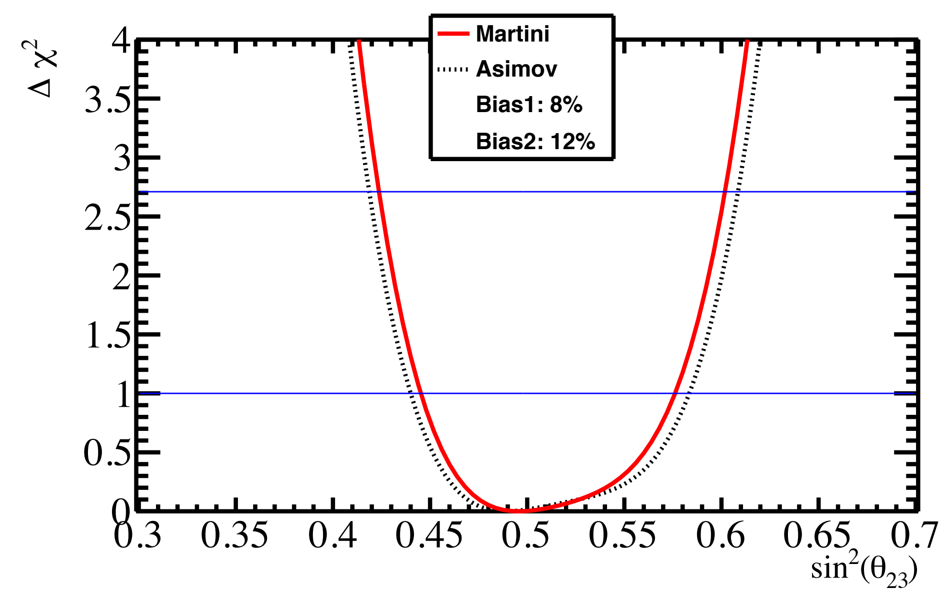
(a) $|\Delta m^2_{32}|$



(b) $sin^2(\theta_{13})$



(c) δ_{cp}



(d) $sin^2(\theta_{23})$

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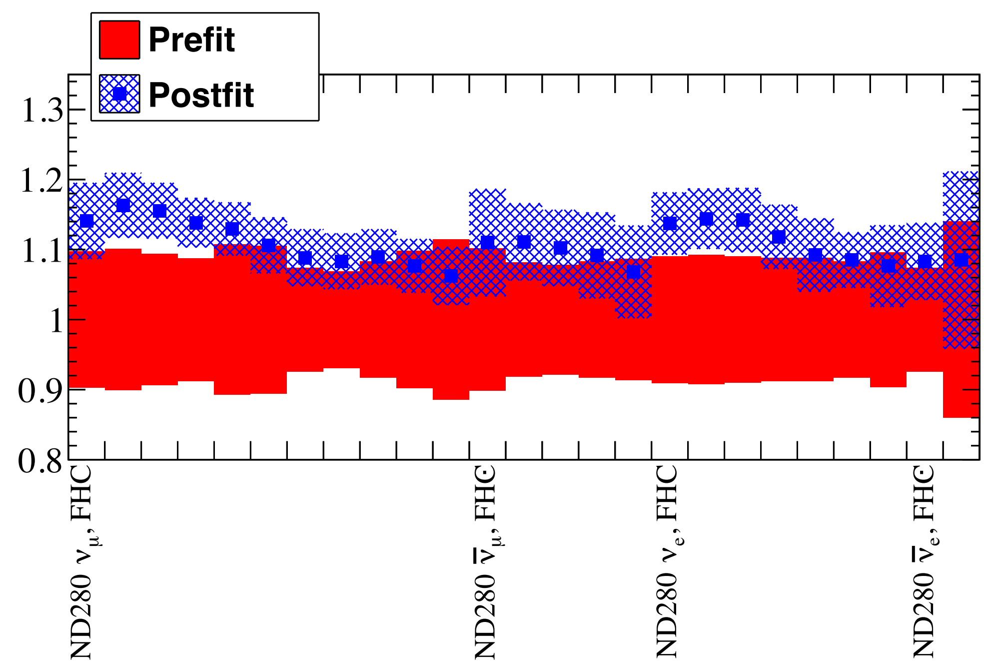
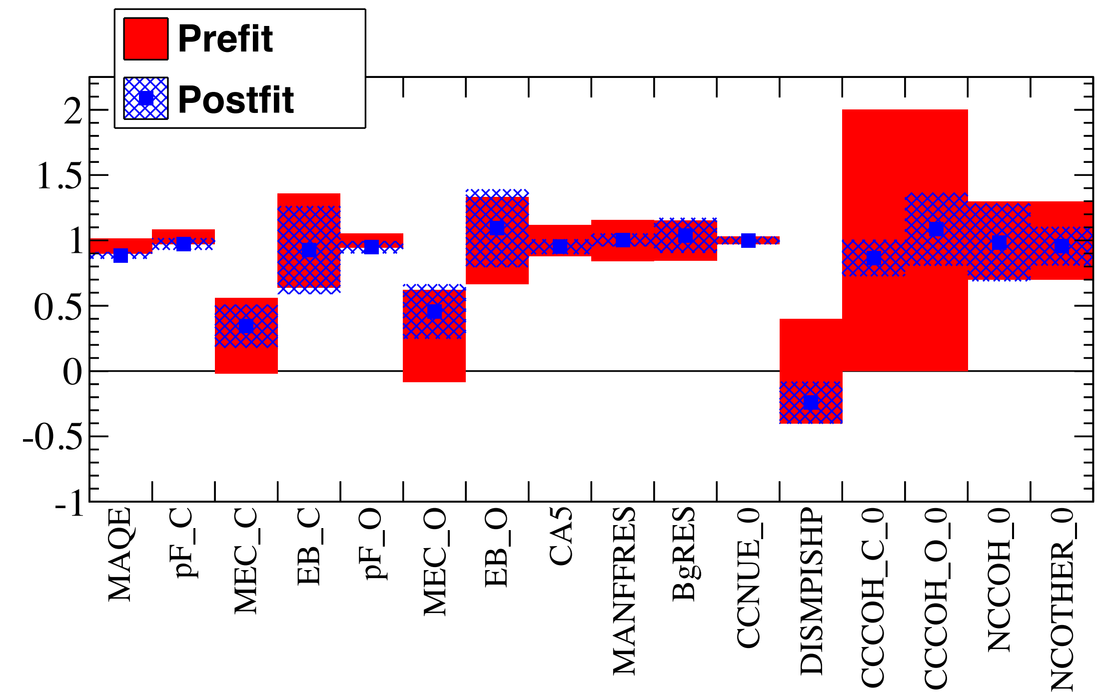
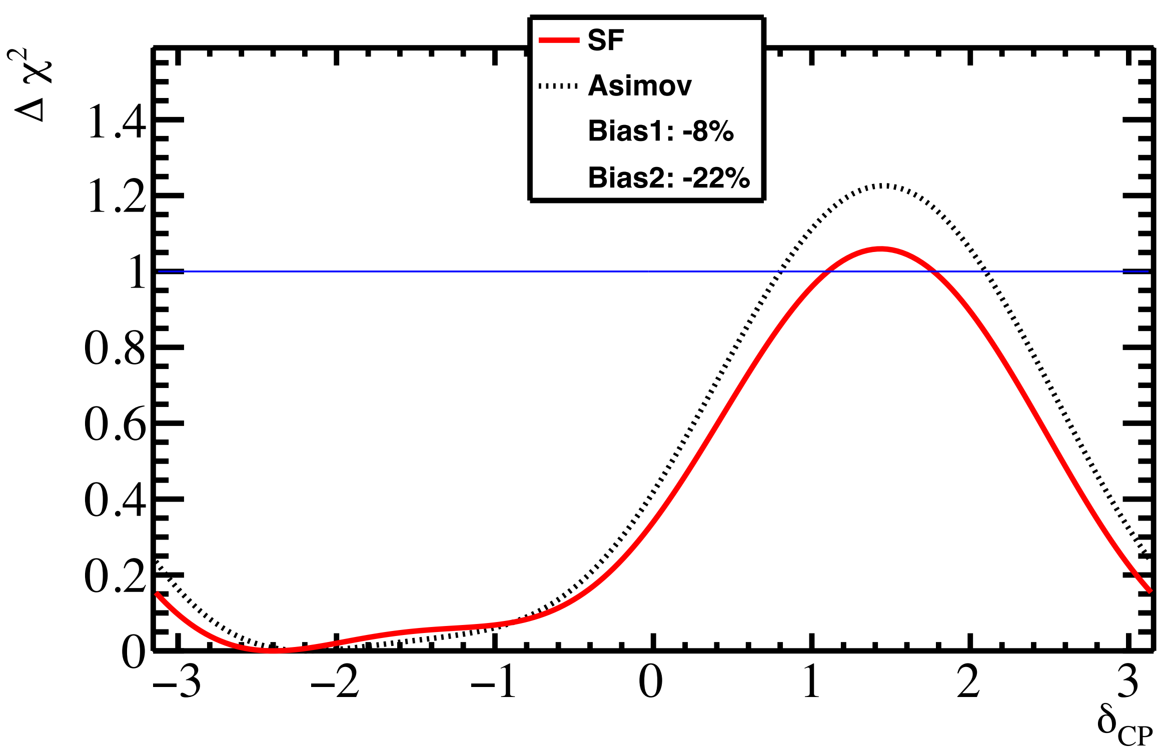
Spectral Function

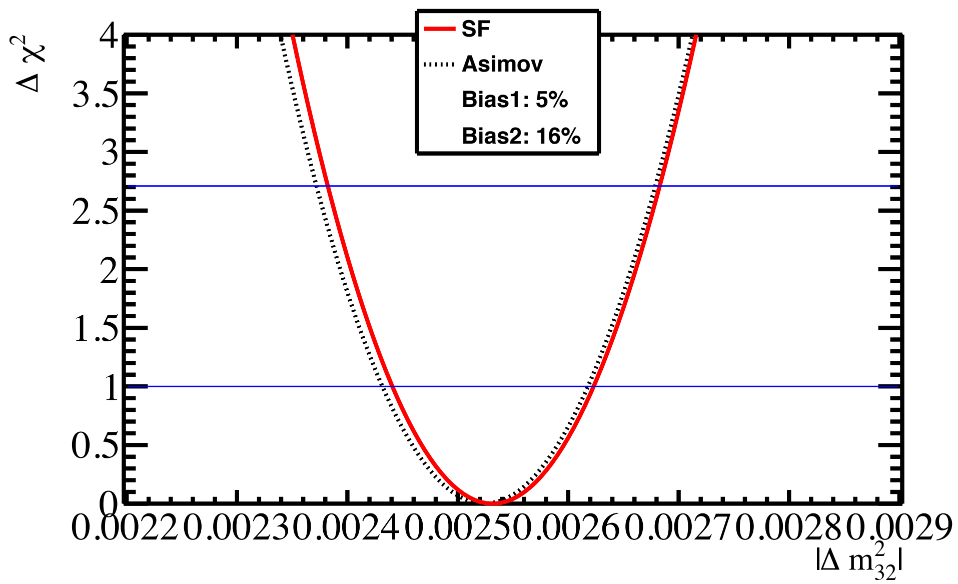






Differences here tend to be smaller; no special uncertainty added

Spectral Function



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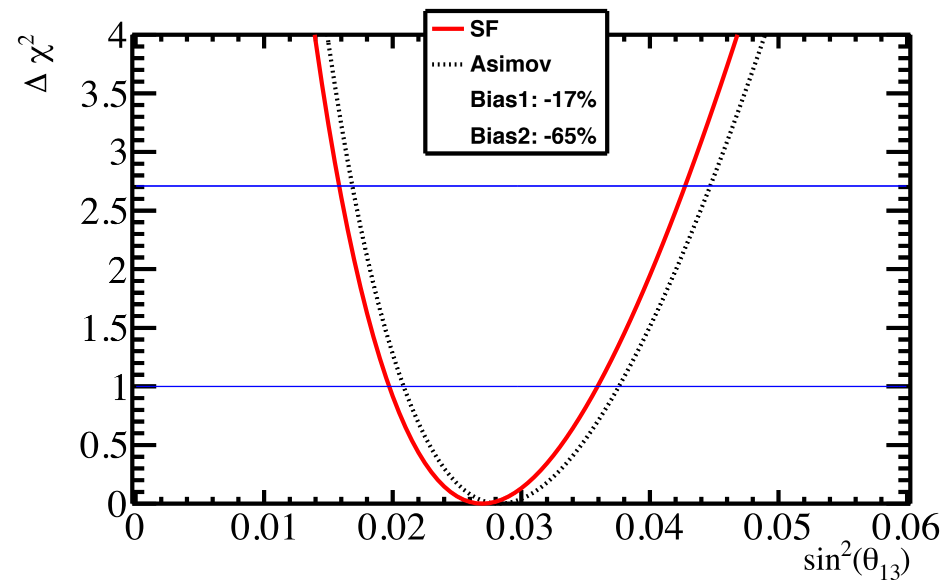
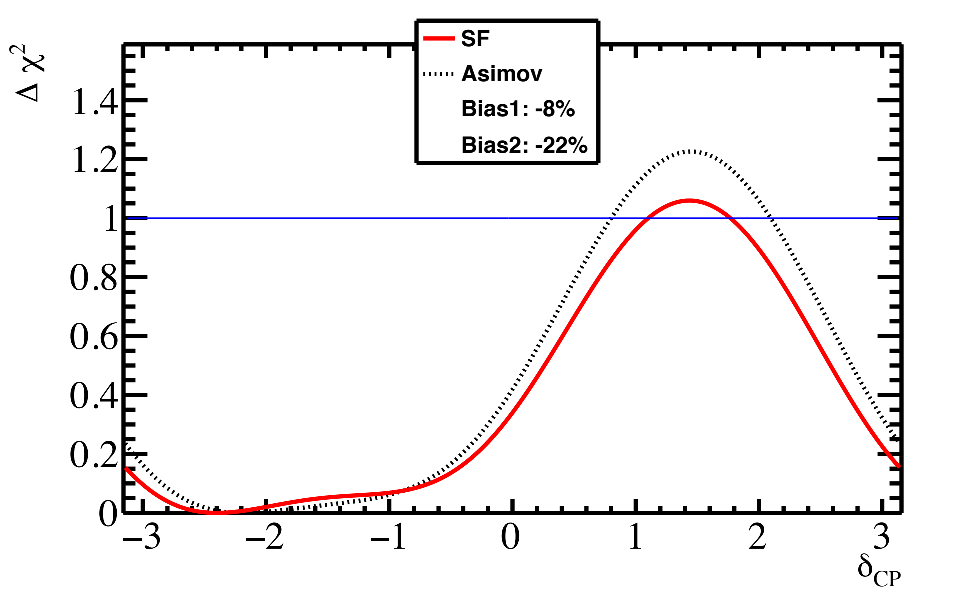
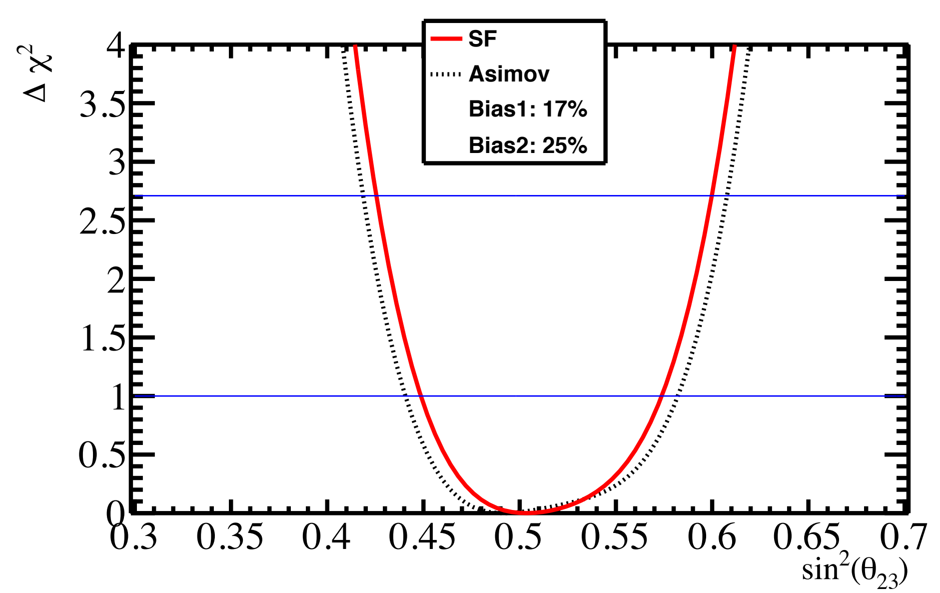


(b) $sin^2(\theta_{13})$



(c) δ_{cp}



(d) $sin^2(\theta_{23})$

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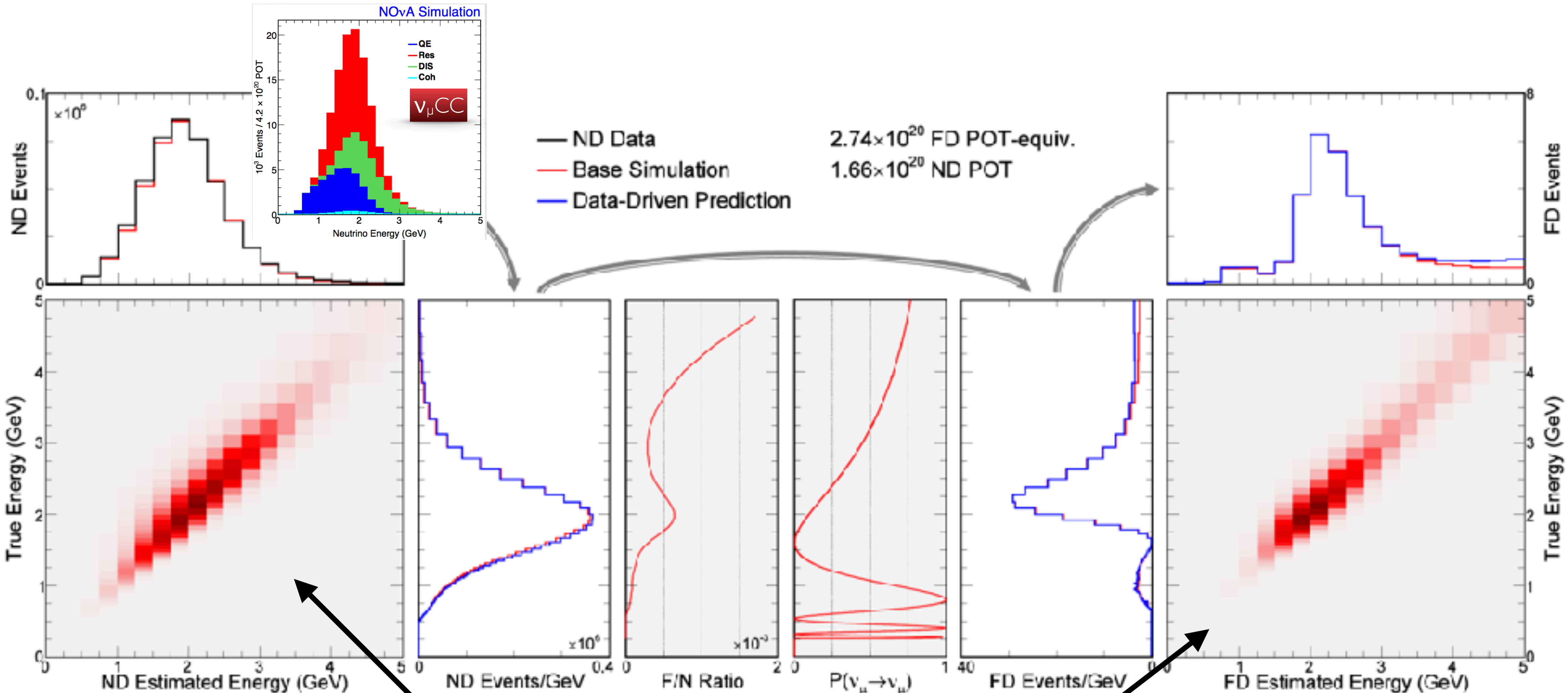
A Note on NOvA



Cross section model dependence is here

Conclusions and Pleas

- Current data statistics seem to indicate that we can hide behind statistical errors for model differences at the moment, but that day ends soon!
- Fake data sets, though an imperfect tool, are extremely important for testing how sensitive oscillation analyses are to cross section models
- Plea: if you release a model, make sure it has the hadronic side!
- Plea: Models that come with reasonable sets of uncertainties are more likely to be used!
- Plea: Help us check our generators!

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