Constraining Systematics at T2K with Near-Detector Fits

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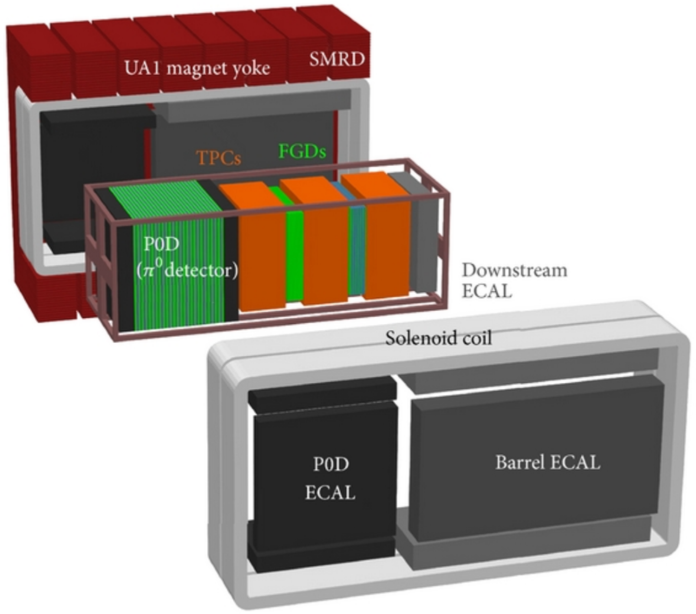
T2K

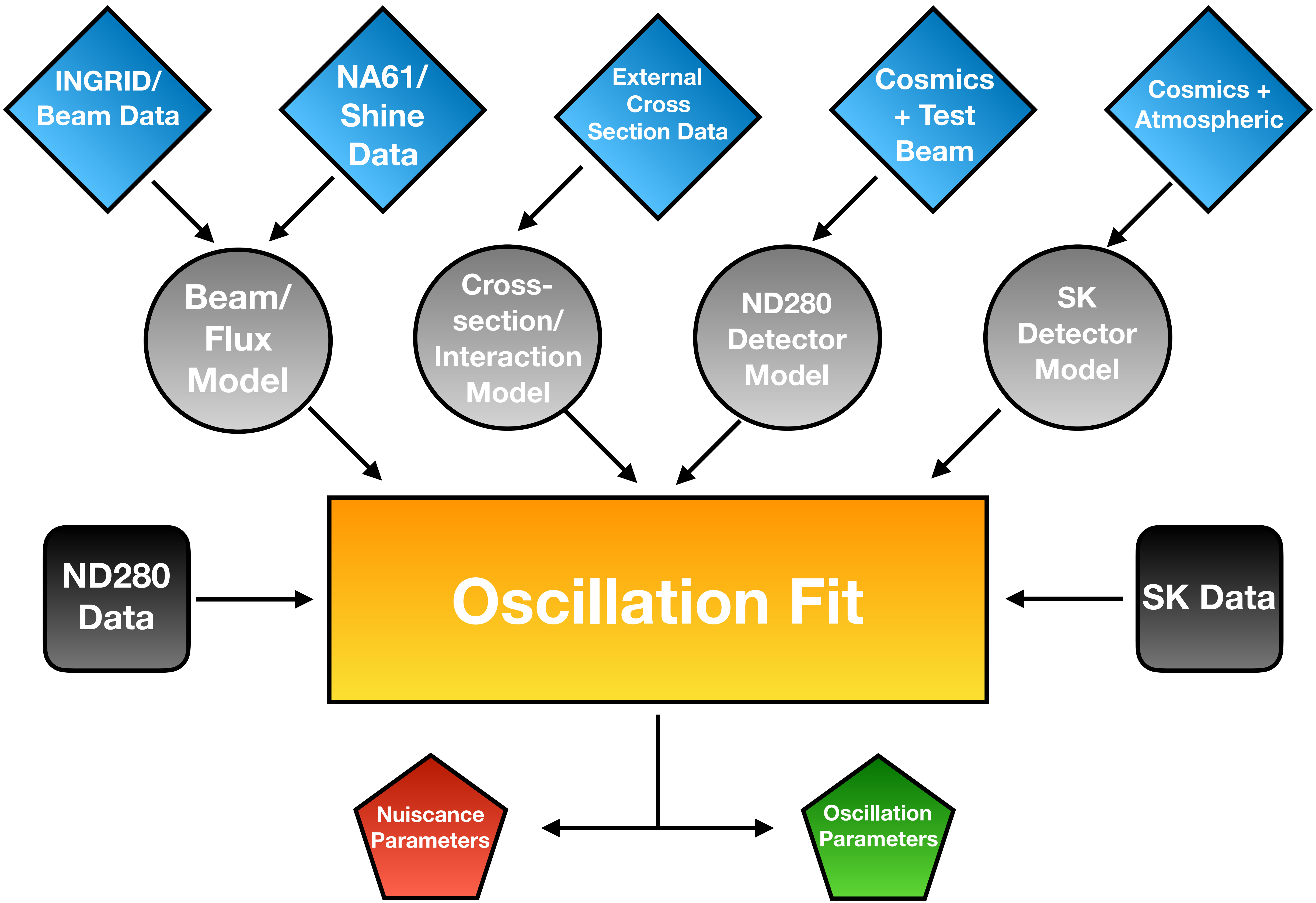


- Long baseline neutrino oscillation experiment in Japan
- Accelerator at J-PARC produces neutrino beam in Tokai on east coast
- Near detector makes flux and cross section measurements 280m up stream
- Super Kamiokande, 295km away in the west, measures neutrinos after oscillations
- World leading measurements of θ_{23}, Δm^2_{32}, δ_{CP}, and mass hierarchy
- If δ_{CP} non-zero, neutrinos are another source of CP violation

Markov **Ch**ain for **3** Flavour Oscillations

- MaCh3 is one of the oscillation analysis frameworks at T2K
- Jointly fit **ND280** and **SK** data
- Neutrino flux, cross-section, ND280 and SK detector systematics, and **oscillation parameters** all fitted to data
  - ~**700** parameters in total
  - High dimensionality, correlations, and boundaries
- Sample the parameter space using **Markov Chain Monte-Carlo**

Analysis Strategy



Near Detector Only Fits

Near Detector Only

$$N_\nu(\overrightarrow{\boldsymbol{X}}) \approx \Phi(E_\nu) \cdot \sigma(E_\nu, \overrightarrow{\boldsymbol{X}}) \cdot \epsilon(\overrightarrow{\boldsymbol{X}}) \cdot P(\nu_\alpha \rightarrow \nu_\beta)$$

Near Detector + SK

- Models take us from observables (e.g. p_μ, θ_μ) to E_ν, which determines oscillation parameters
- Fit only near detector data to constrain flux and cross section model uncertainties, and validate against other analysis groups
- Near detector fit reduces uncertainty on event rate prediction at SK significantly
- Can also shift predicted event spectrum, must be fully understood

2018 Analysis Uncertainties

SK Samples →

Sample	w/o ND280	w/ND280
Muon Neutrino	14.6%	5.1%
Muon Anti-Neutrino	12.5%	4.5%
Electron Neutrino	16.9%	8.8%
Electron Anti-Neutrino	14.4%	7.1%

Near Detector Postfit

- Extract postfit values by marginalising over all but one parameter, one by one
- Constraint on systematics comes almost entirely from near detector fit
- Full posterior propagated to make SK event rate predictions

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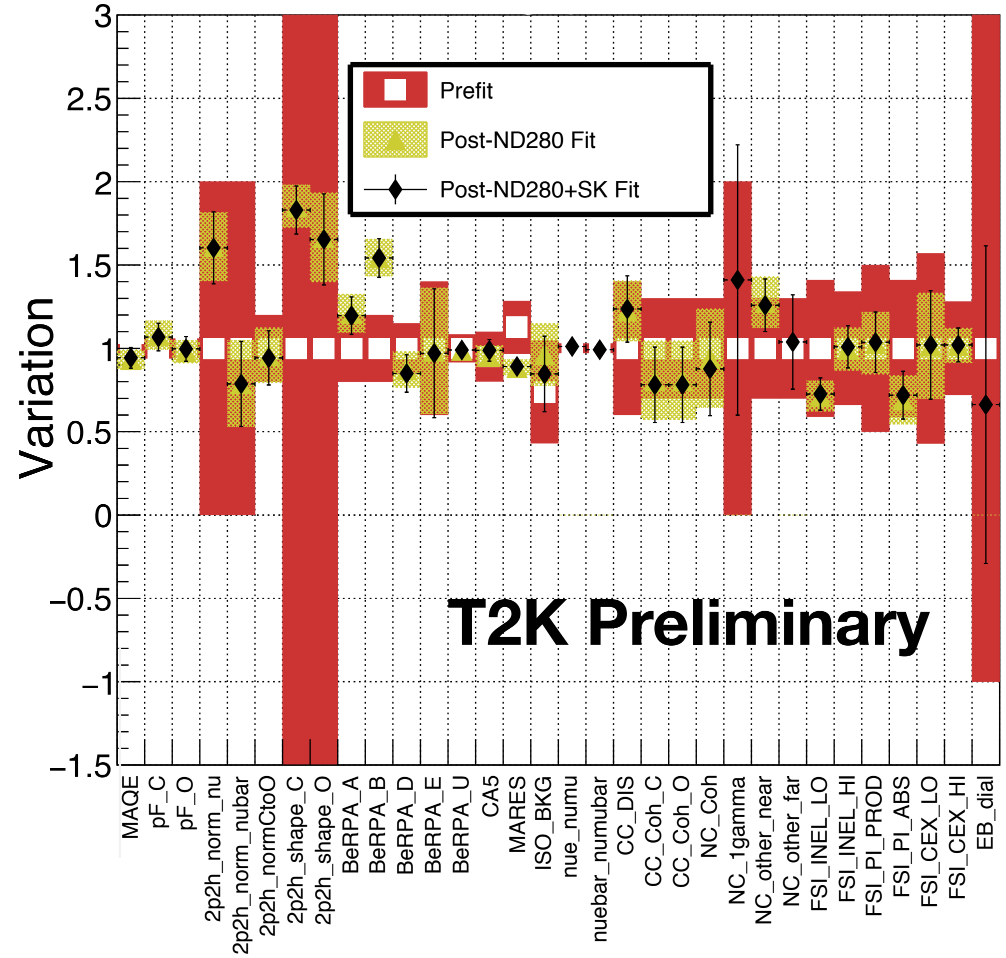
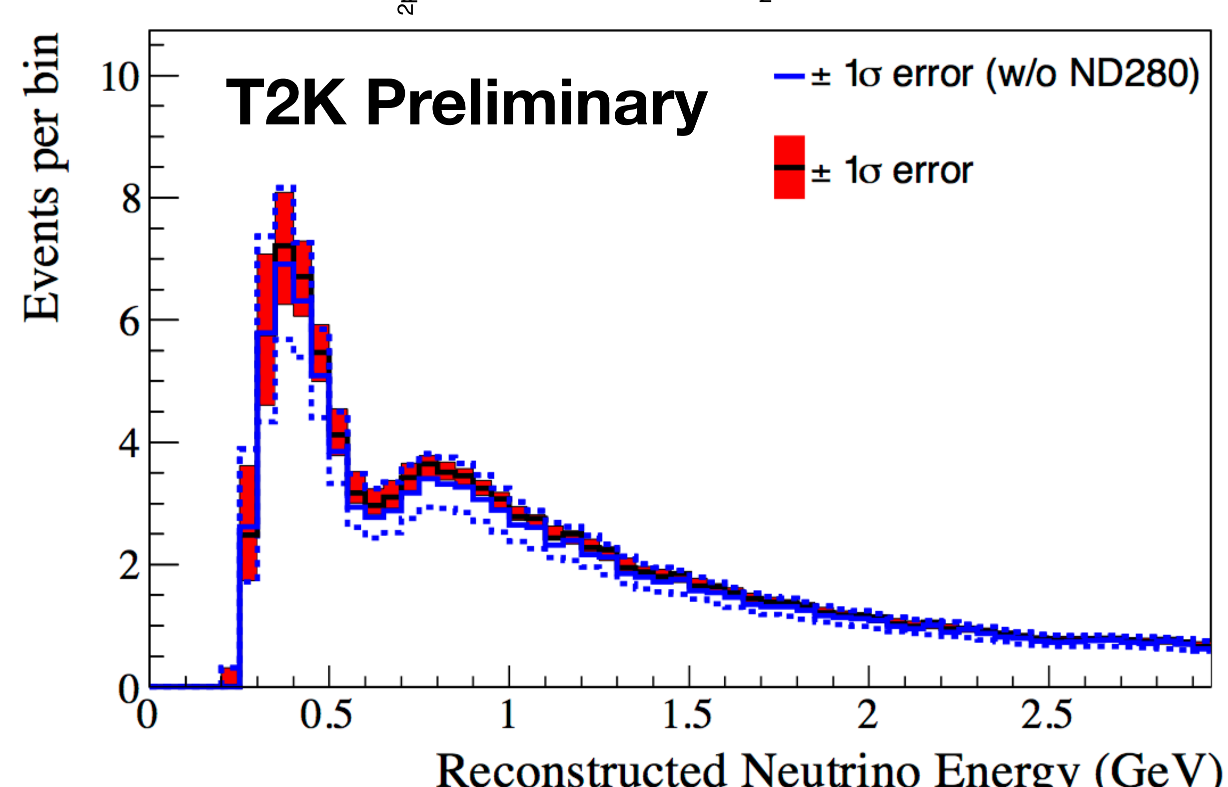


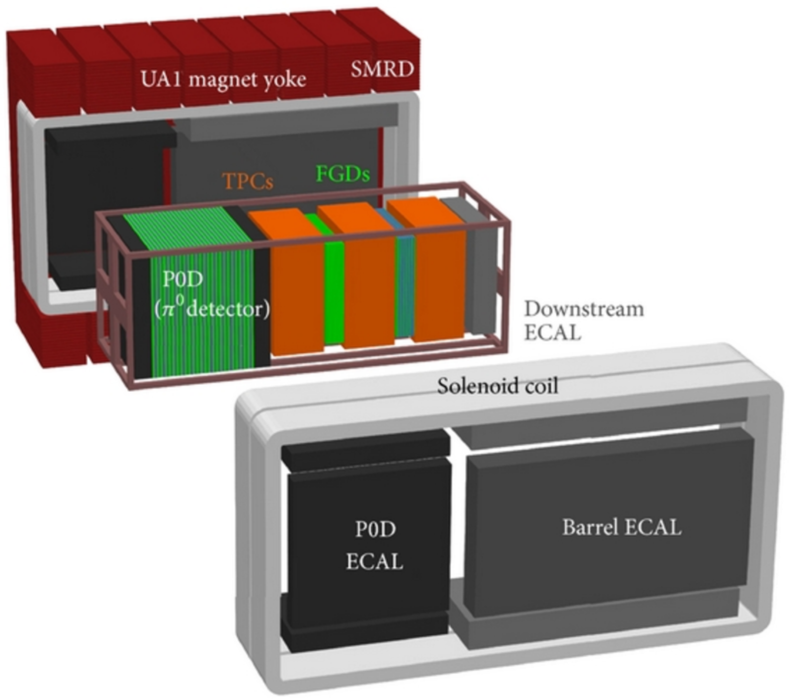


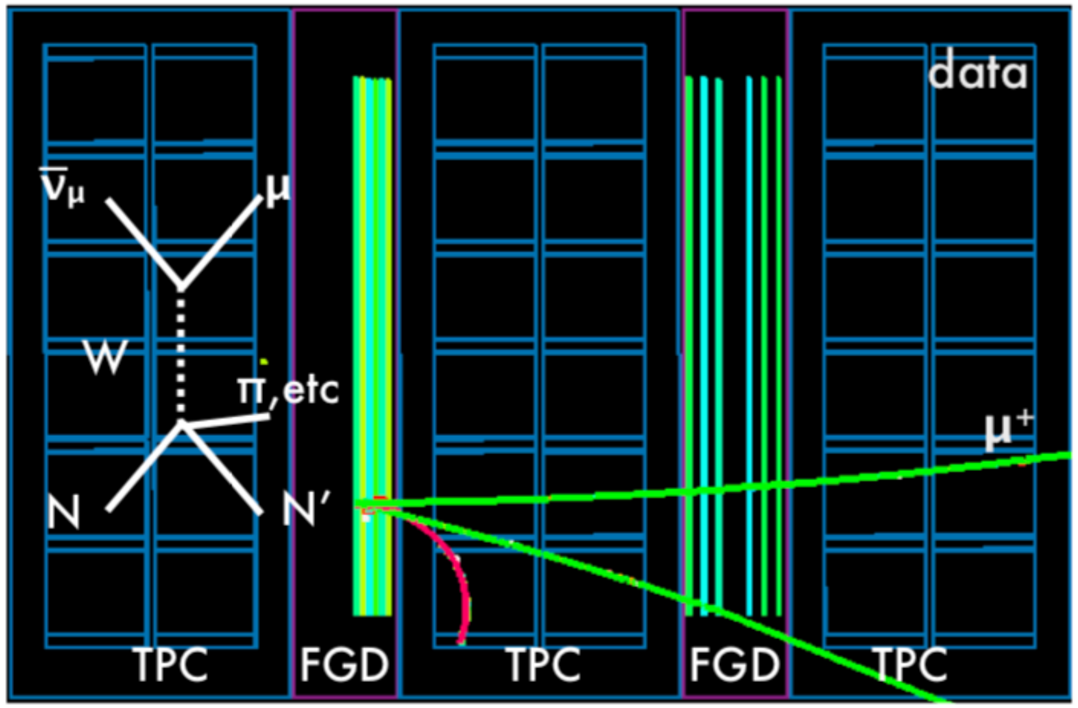
Updates for 2019 Analysis

- Updated interaction model:
  - Energy dependent 2p2h, where the neutrino interacts with a correlated pair of nucleons model
  - Deep Inelastic Scattering + Multi Pi model improvement
- Reduced flux uncertainties
- Significantly increased data
- Expect significant improvement to analysis!

New Anti-Neutrino Samples

- Split data into different samples based on event topology. Different systematics apply to different samples
- Previously split anti neutrino data by number of tracks, with more data can split by number of pions
  - Now anti-neutrino samples match neutrino: CC0π, CC1π, CCOther
  - Splits the N-track anti-neutrino selection so single-pion, multi-pion, Final State Interactions, and Deep Inelastic Scattering systematics are constrained from separate samples





New Treatment of Binding Energy

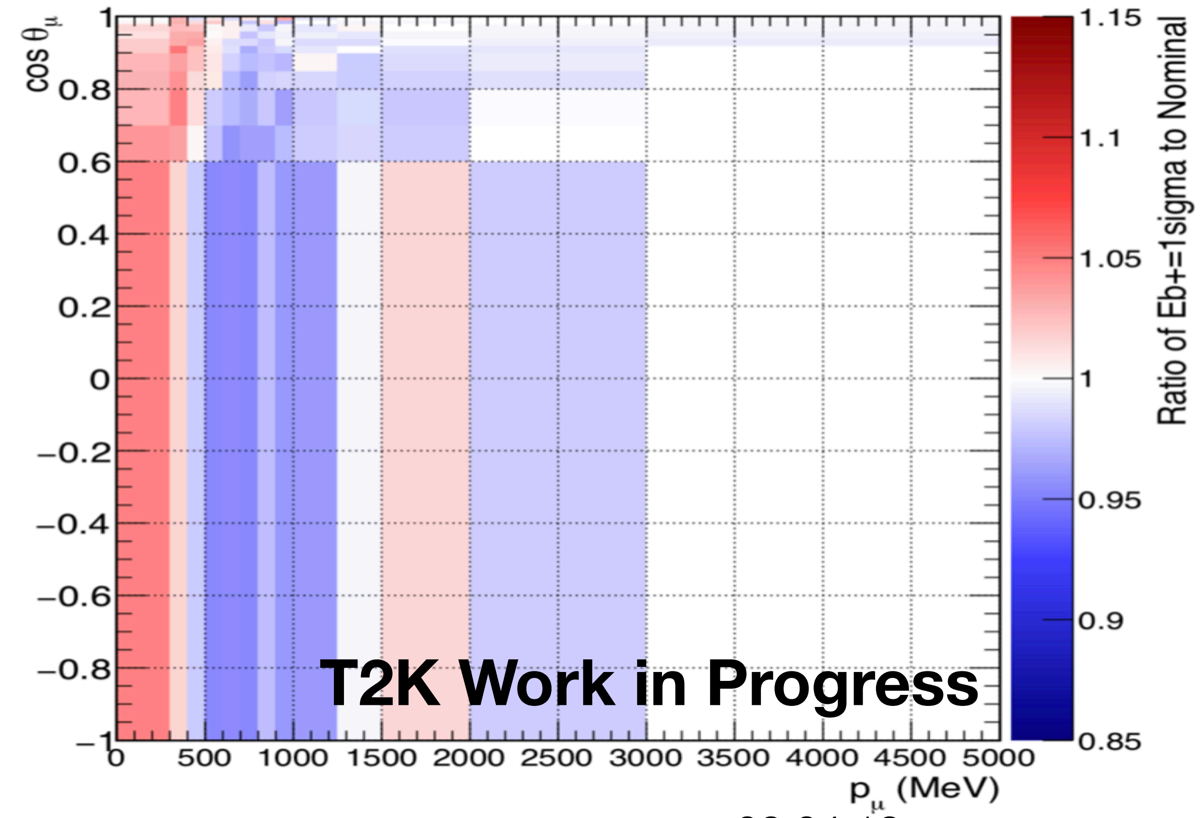
- Measure lepton momentum and angle at ND280, can then reconstruct neutrino energy
- If binding energy of target nucleus not modelled correctly we miscalculate E_ν
- New parameter translates change in binding energy to shift in lepton momentum
- Correlates highly with other parameters and has non-gaussian posterior - must be understood

$$E_\nu^{reco} = \frac{m_f^2 - m_i'^2 - m_l^2 + 2m_i' E_l}{2(m_i' - E_l + p_l \cos\theta_{\nu,l})}$$

$$m_i' = m_i - E_b$$

i = initial state nucleon
f = final state nucleon
l = final state lepton

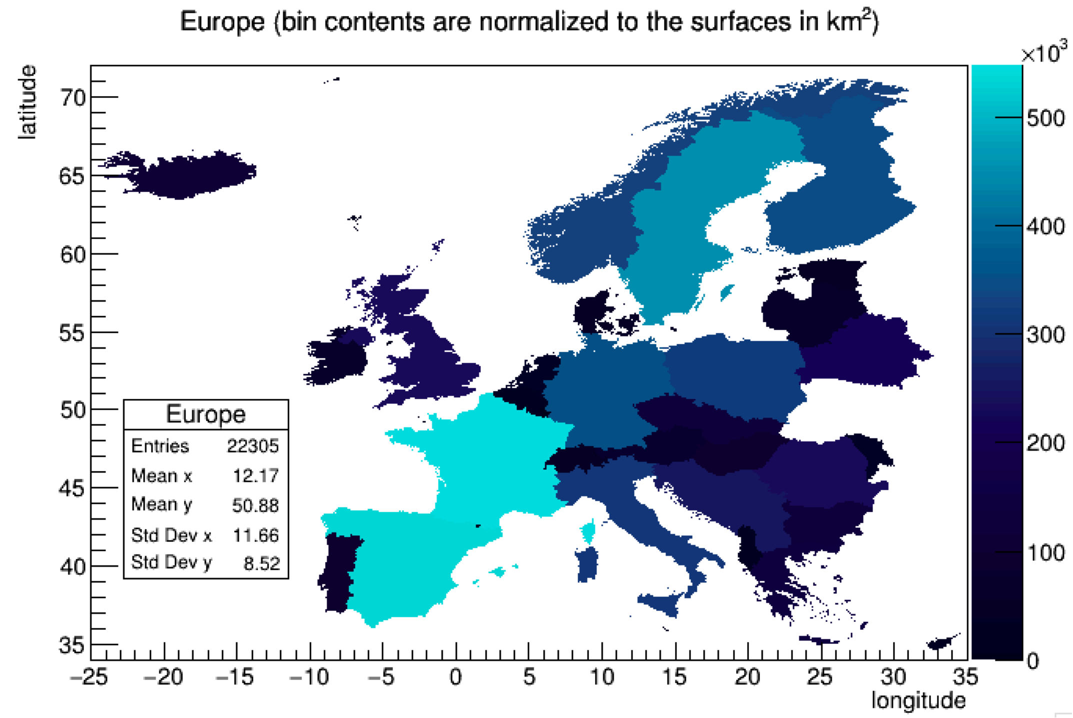
Ratio of Eb += 1 sigma to Nominal



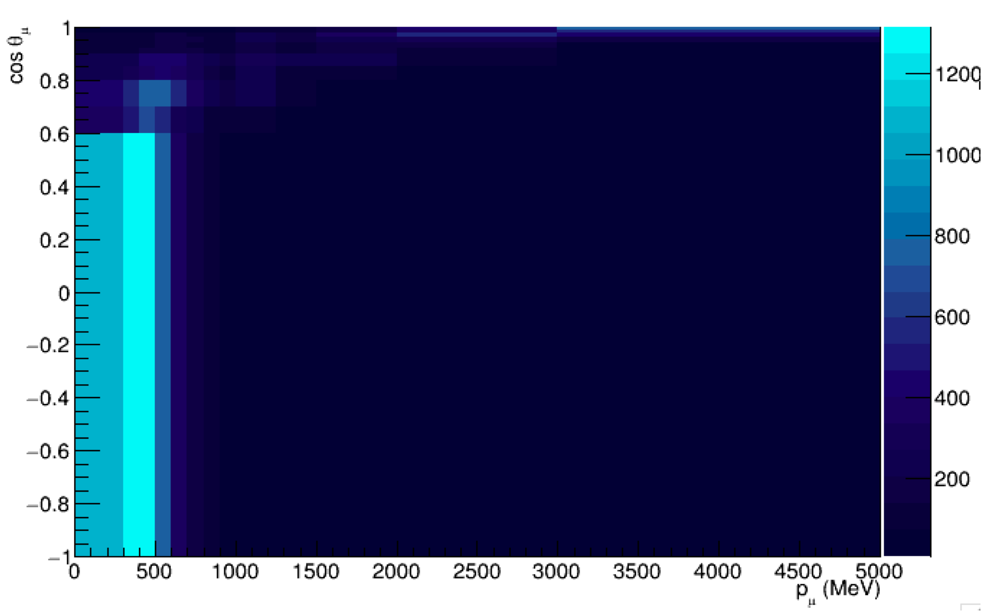
Non-Rectangular Fit Binning

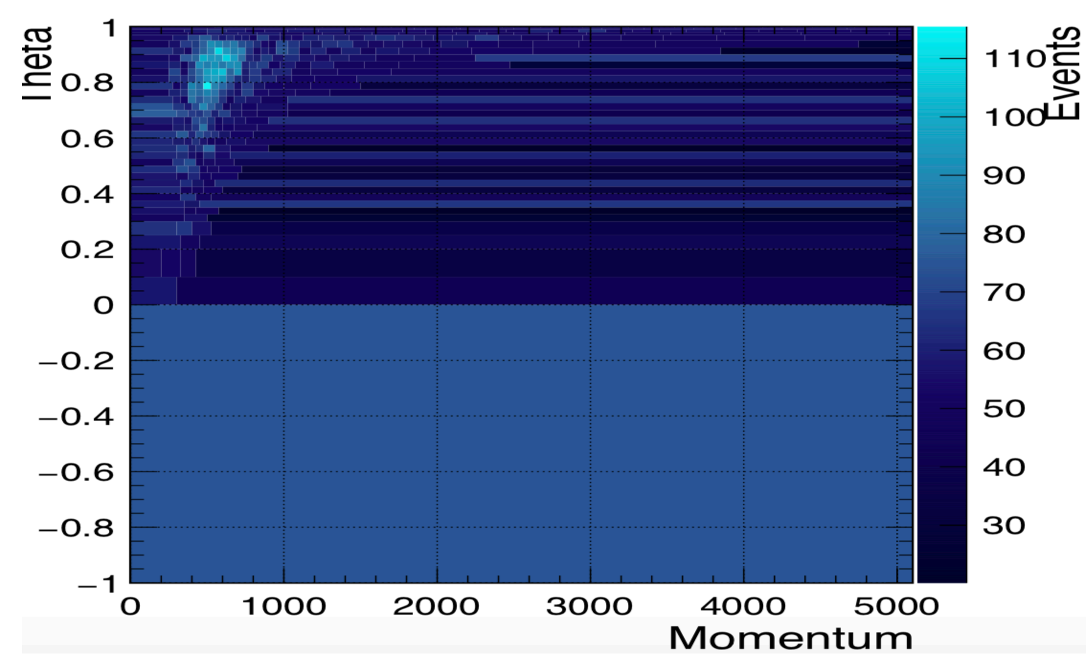
- Binning choice is a trade-off:
  - Enough events to reduce statistical error
  - Good resolution in peak regions
- Uniform rectangular:
  - Thin bins outside region of interest
  - Larger than necessary bins in peak
- More of a problem with increased stats
- Machinery for arbitrary binning in place, final binning still to be optimised

Non-Rectangular Binning Example



* borders accurate as of 1992

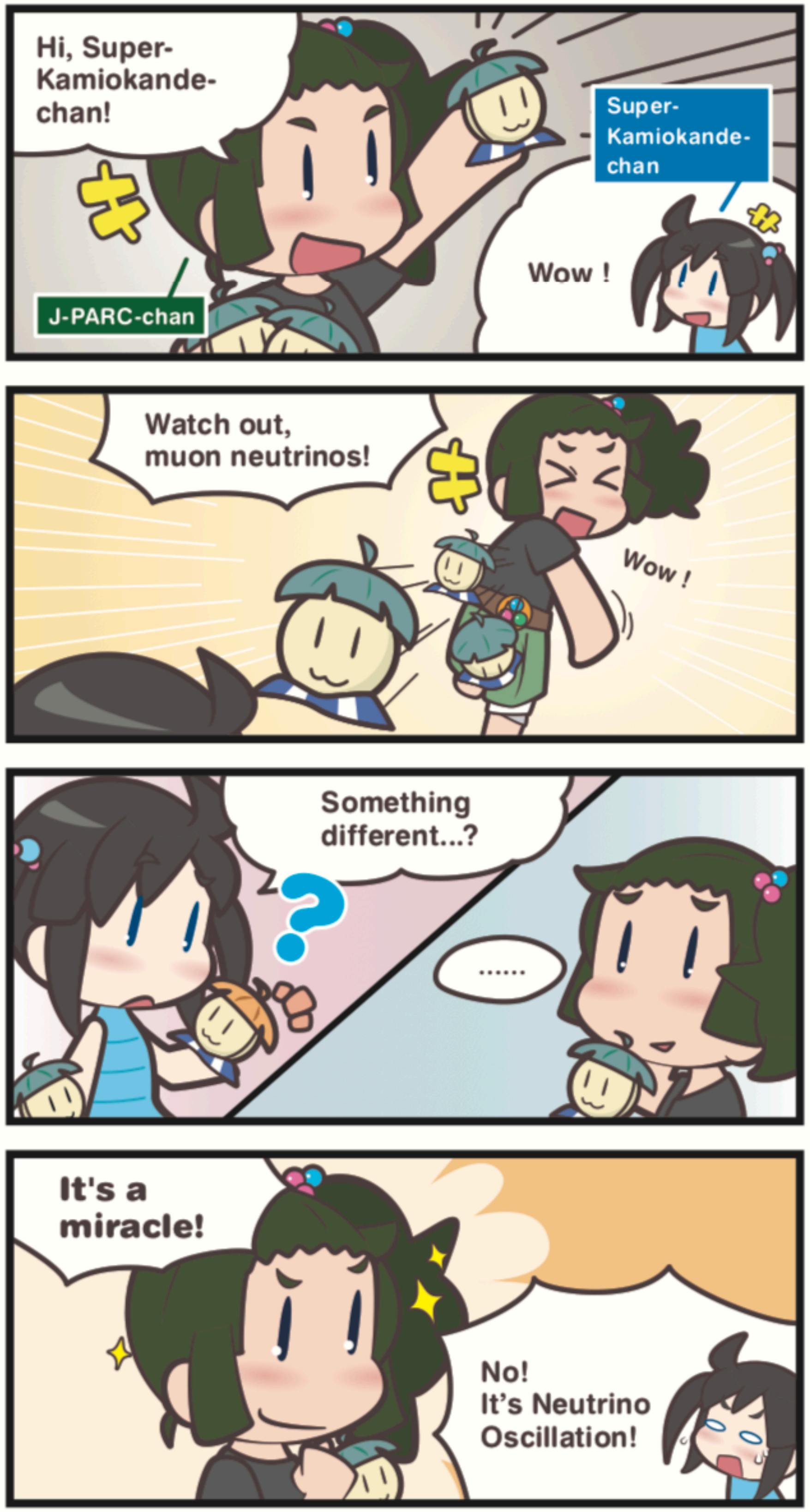




Outlook

- Near detector fits crucial to reducing systematics and allowing T2K to continue to make world leading neutrino oscillation measurements
- Updates to binding energy, anti neutrino samples, fit binning already happening for 2019 analysis
- Still to come:
  - Updated interaction model: energy dependent model for neutrino interactions with a correlated pair of nucleons, improved Deep Inelastic Scattering + Multi Pi model
  - Increase in data: doubling neutrino + anti neutrino data with addition of new runs
  - Latest tuning of systematics
  - Increased acceptance (4pi samples) for future analyses

Thanks for listening!



https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/index.html

Backups

Likelihood Calculations

- Number of events in each bin modelled as poisson distributed
- Systematics modelled as Gaussian (MAQE, 2p2h norm, pF, 2p2h shape flat priors)

$$-\ln L = -\ln L_{samples} - \ln L_{systematics}$$

$$-\ln L = \sum_{i=1}^{n_{bins}} \left(N_i^{MC}(\vec{x}) - N_i^{Data} + N_i^{Data} \ln\left(N_i^{Data}/N_i^{MC}\right)\right) + \sum_{j=1}^{n_{systs}} \sum_{k=1}^{n_{systs}} \Delta x_j (V_x^{-1})_{jk} \Delta x_k$$

Systematics

- 30+ Cross Section parameters for various interaction modes
  - Updated frequently to account for new theoretical calculations
- 100 Flux Parameters
  - Normalisations in bins of E_ν
- 556 ND280 Detector Parameters
  - Normalisations binned in 2D: momentum and angle of final state lepton

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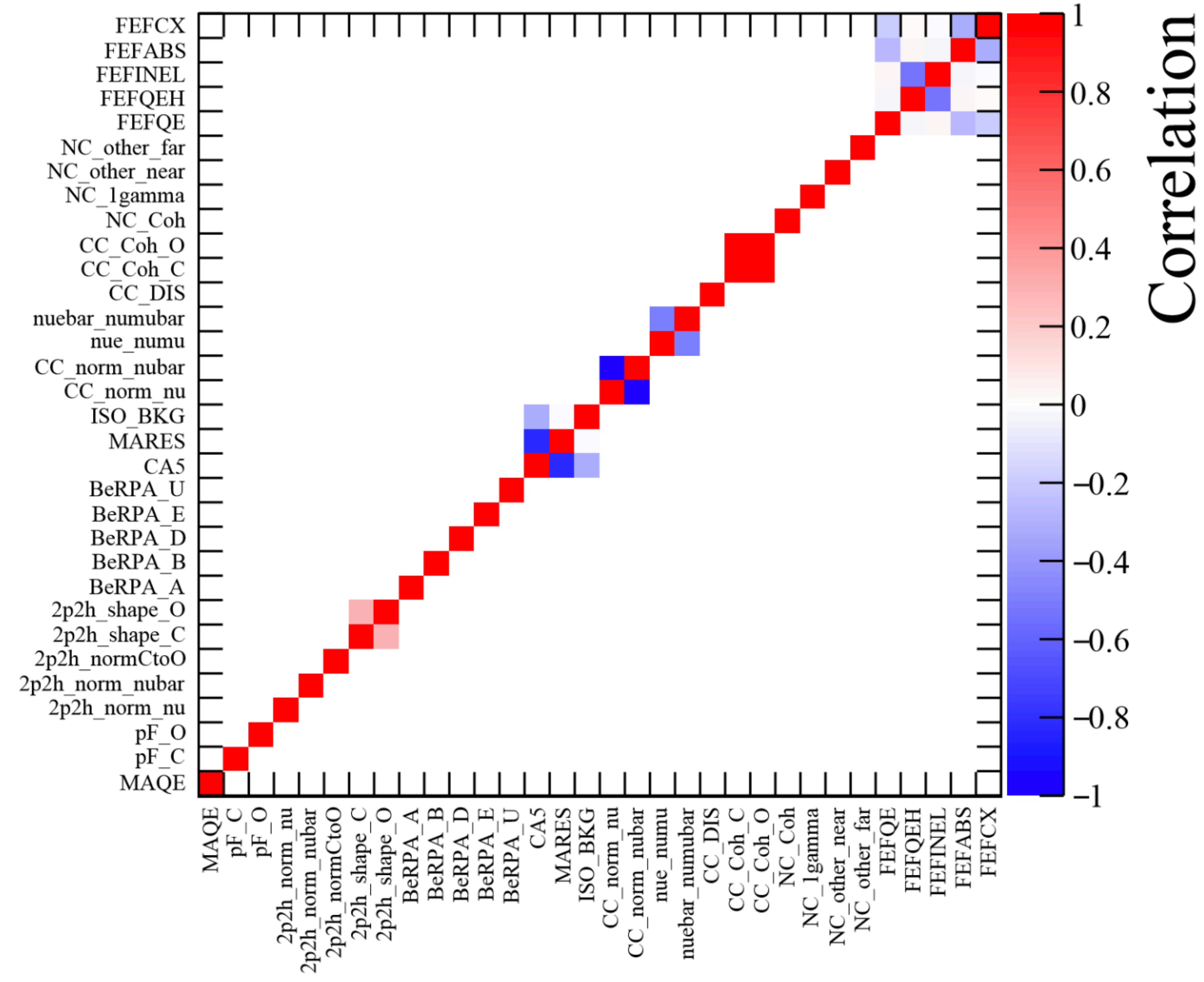
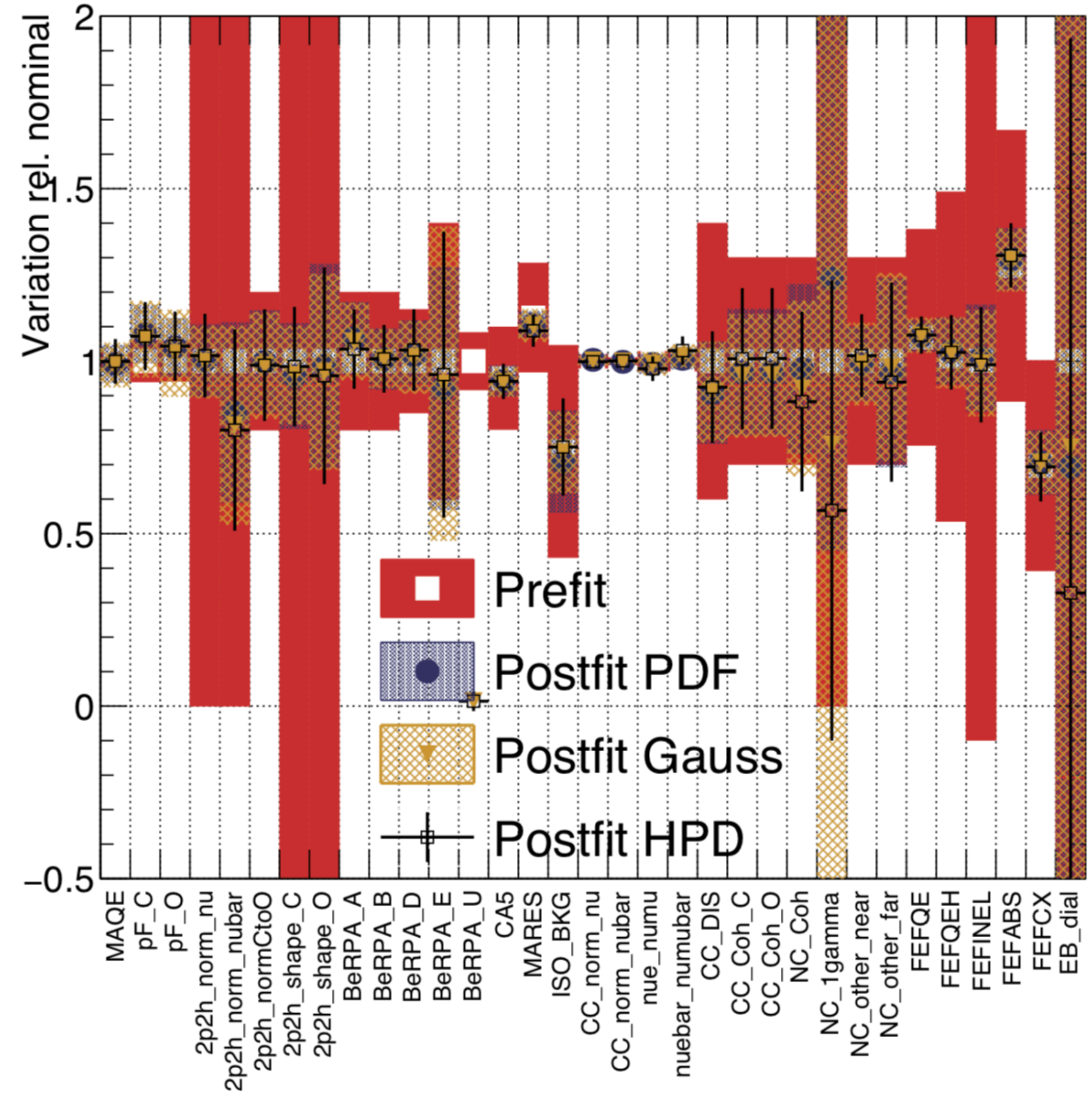
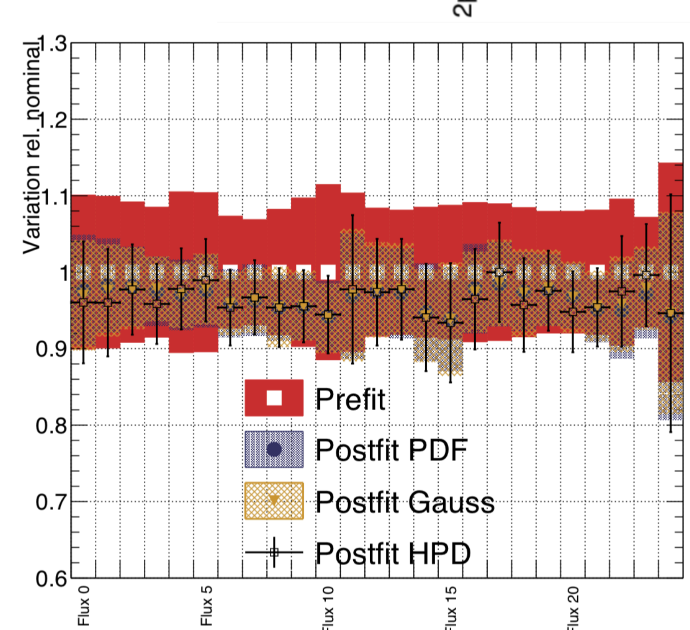
Cross Section Correlation Matrix

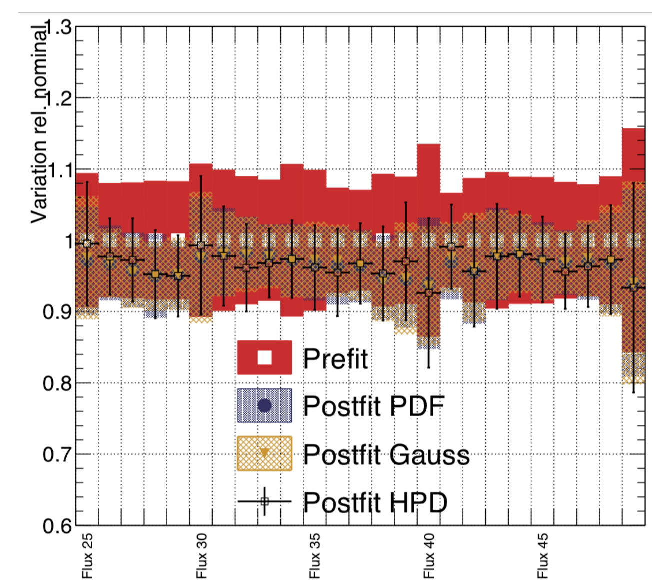


Near Detector Asimovs

- Fitting nominal MC to itself
- Expect to recover nominal parameter values
- Used for validations and sensitivity studies
- Marginalisation causes deviations from nominal
- Cross section and ND flux parameters here

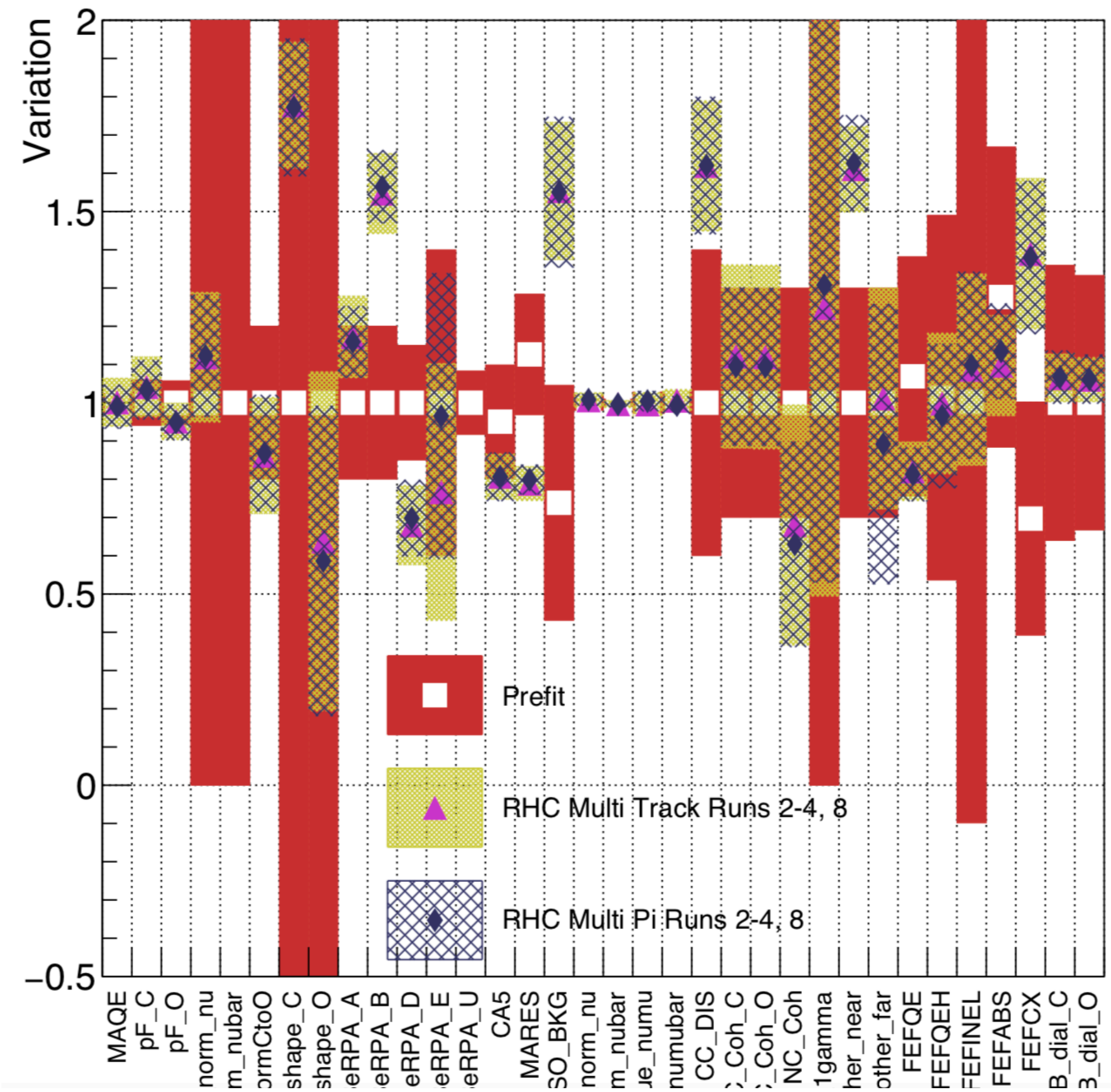


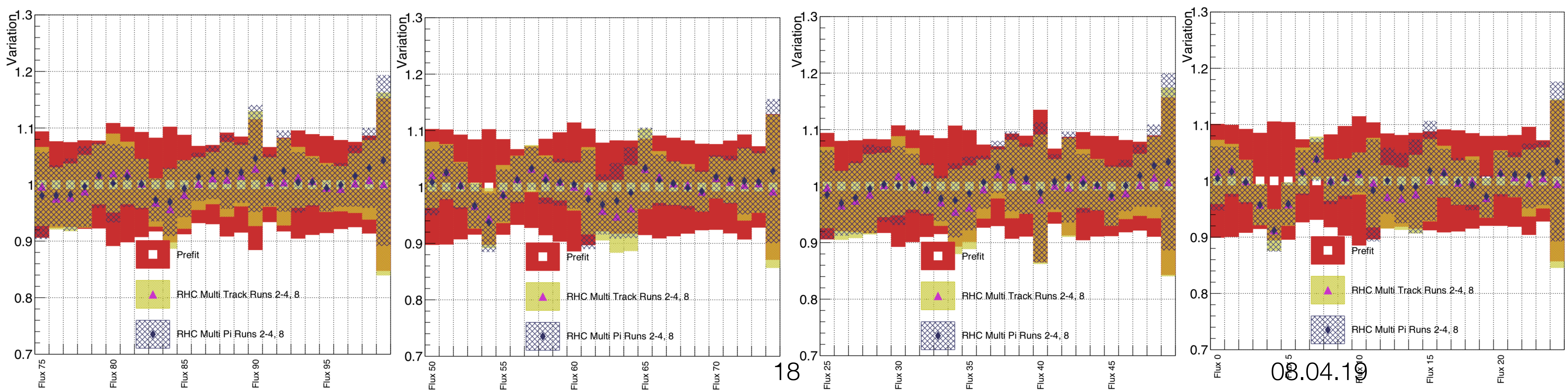




RHC Multi Pion Validation

- New RHC samples should have no effect Runs 2-4, 8
- Fit using FHC only data before and after RHC Multi Pi implementation to sanity check
- Results in good agreement

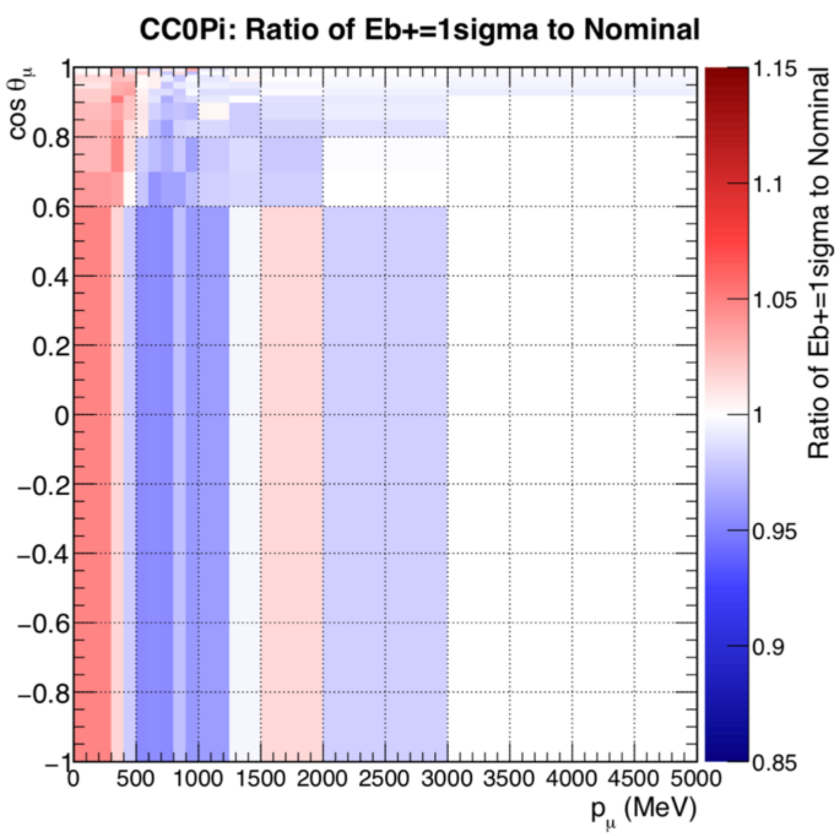




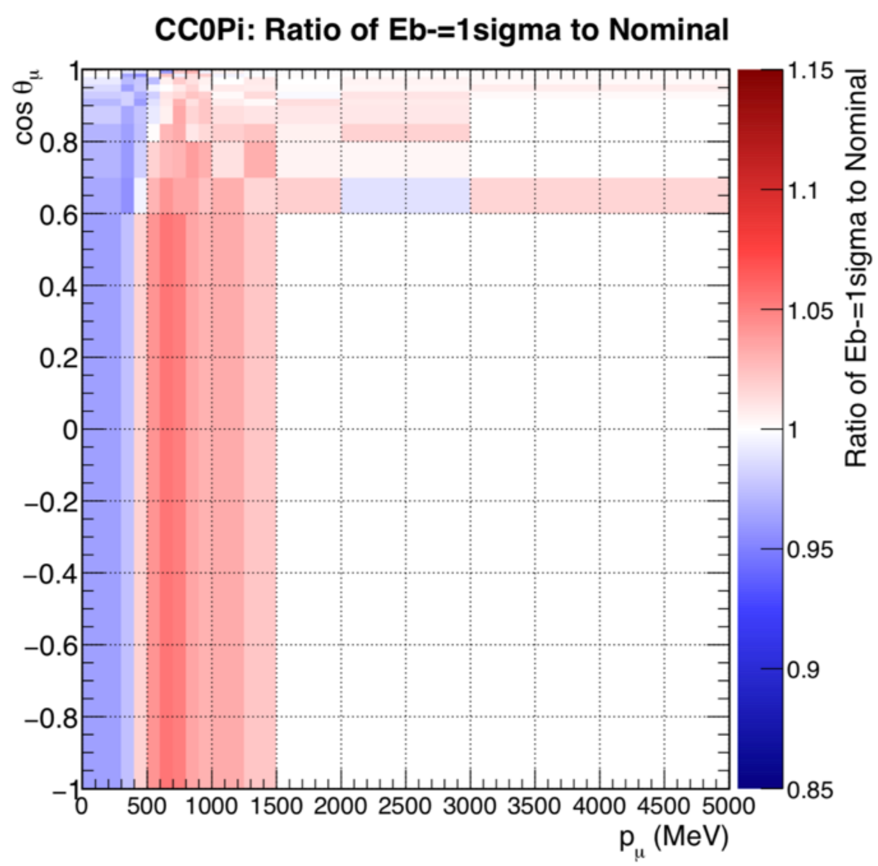
Eb Dial Momentum Shifts

- Momentum shift causes events to migrate in $\mathbf{P}_{\mu}$-cosθ_{μ}. As Eb increases, $\mathbf{P}_{\mu}$ decreases and vice versa
- Similar changes as seen in Eb fake dataset

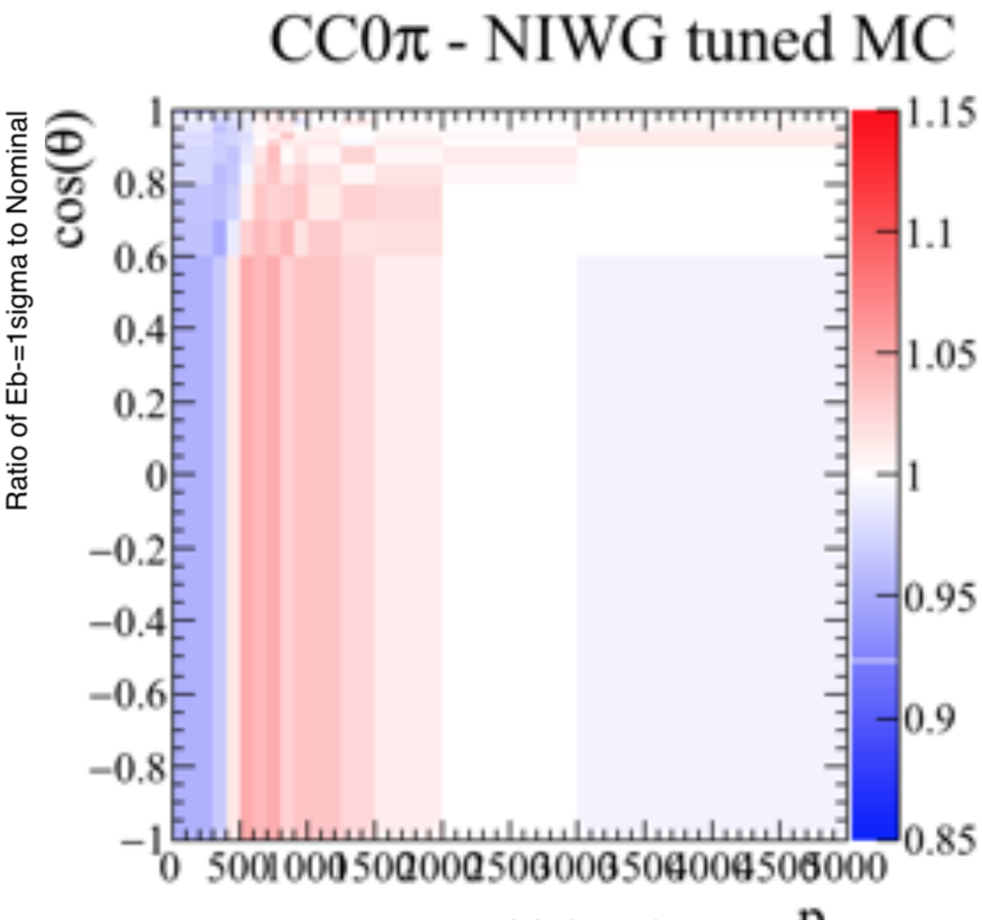
Dial set to +1 Sigma



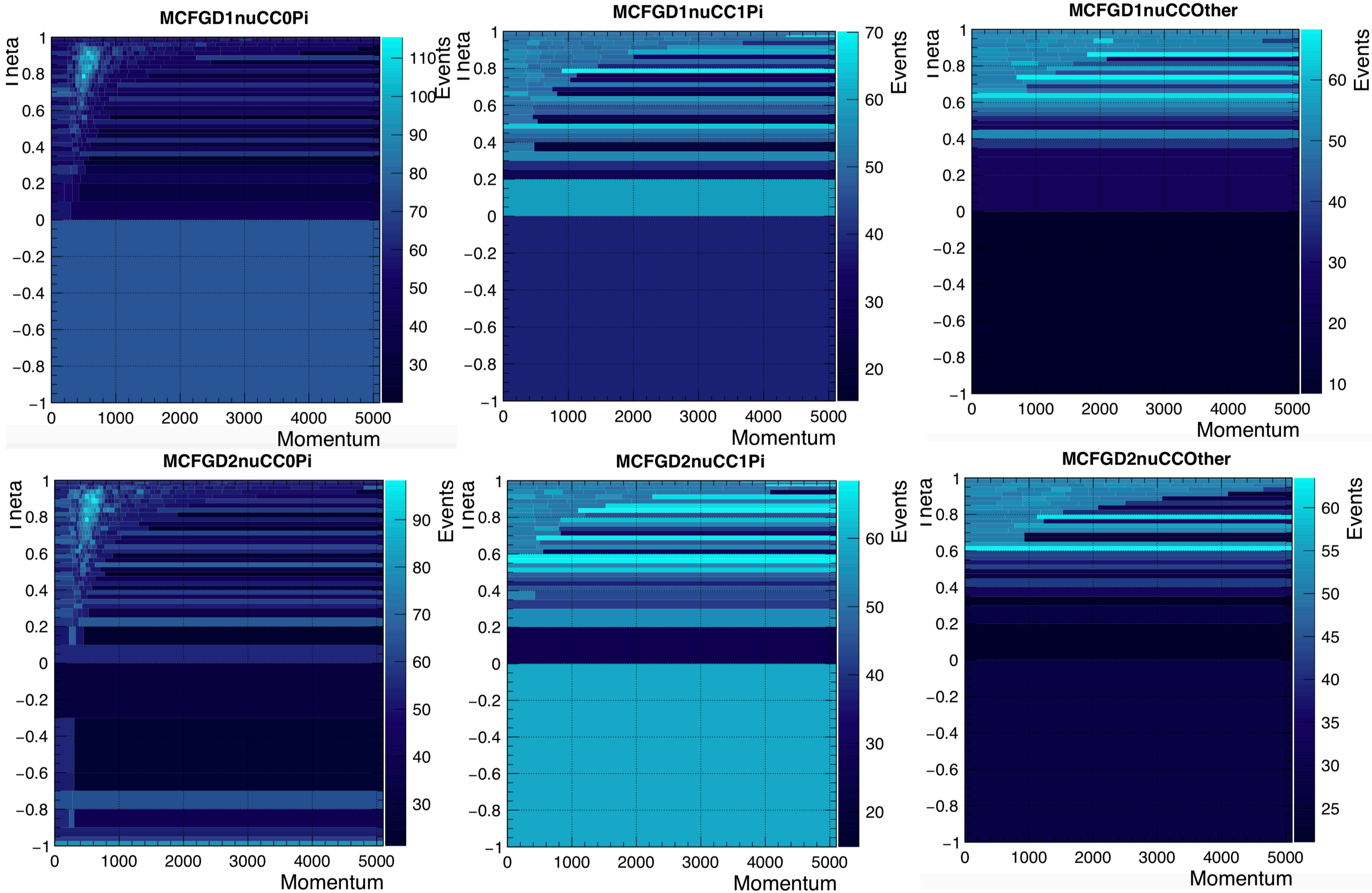
Dial set to -1 Sigma



Eb Fake Dataset



TH2Poly First Pass Binning



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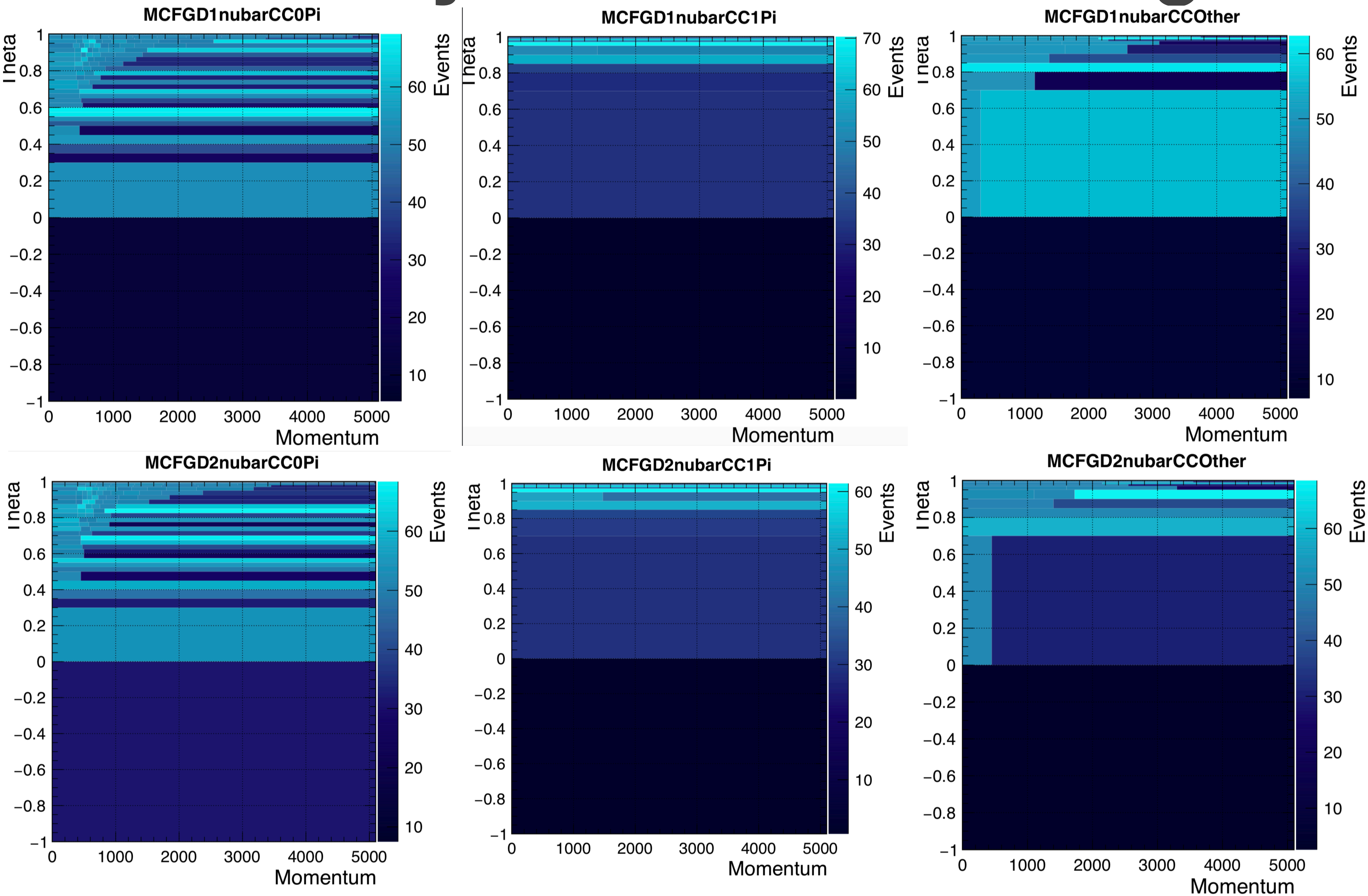

TH2Poly First Pass Binning