THE T2K CROSS-SECTION RESULTS AND PROSPECTS FROM THE OSCILLATION PERSPECTIVE

KYOTO UNIVERSITY
KEIGO NAKAMURA
ON BEHALF OF T2K COLLABORATION

T2K experiment

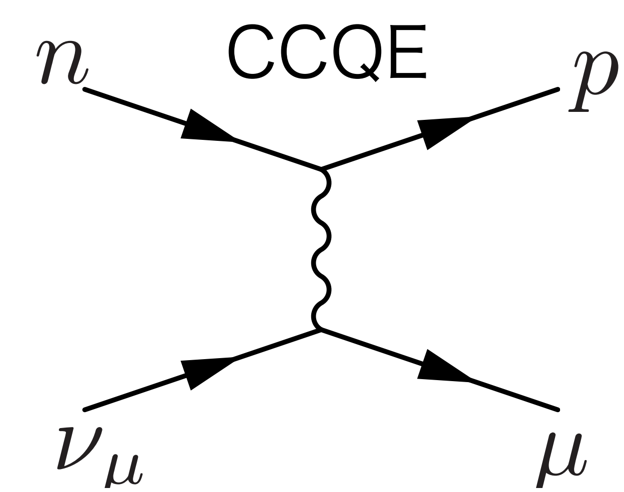
- Muon neutrino/anti neutrino beam is generated at J-PARC accelerator and detected at Super-Kamiokande detector.
- Measure neutrino oscillation parameters
- Neutrino interaction study using near detector

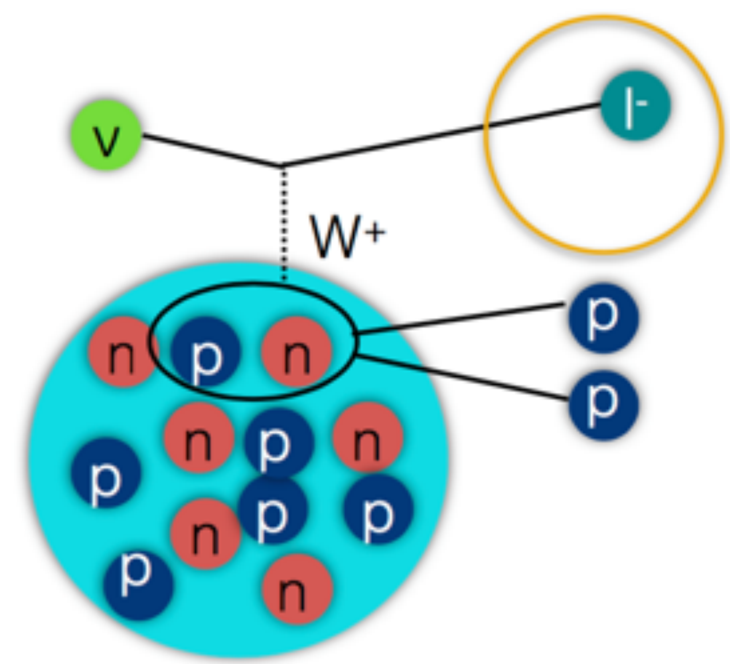
Why Neutrino interaction model is important for neutrino oscillation?

- CCQE interaction is the dominant contribution for T2K.
- Neutrino energy can be reconstructed as:

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

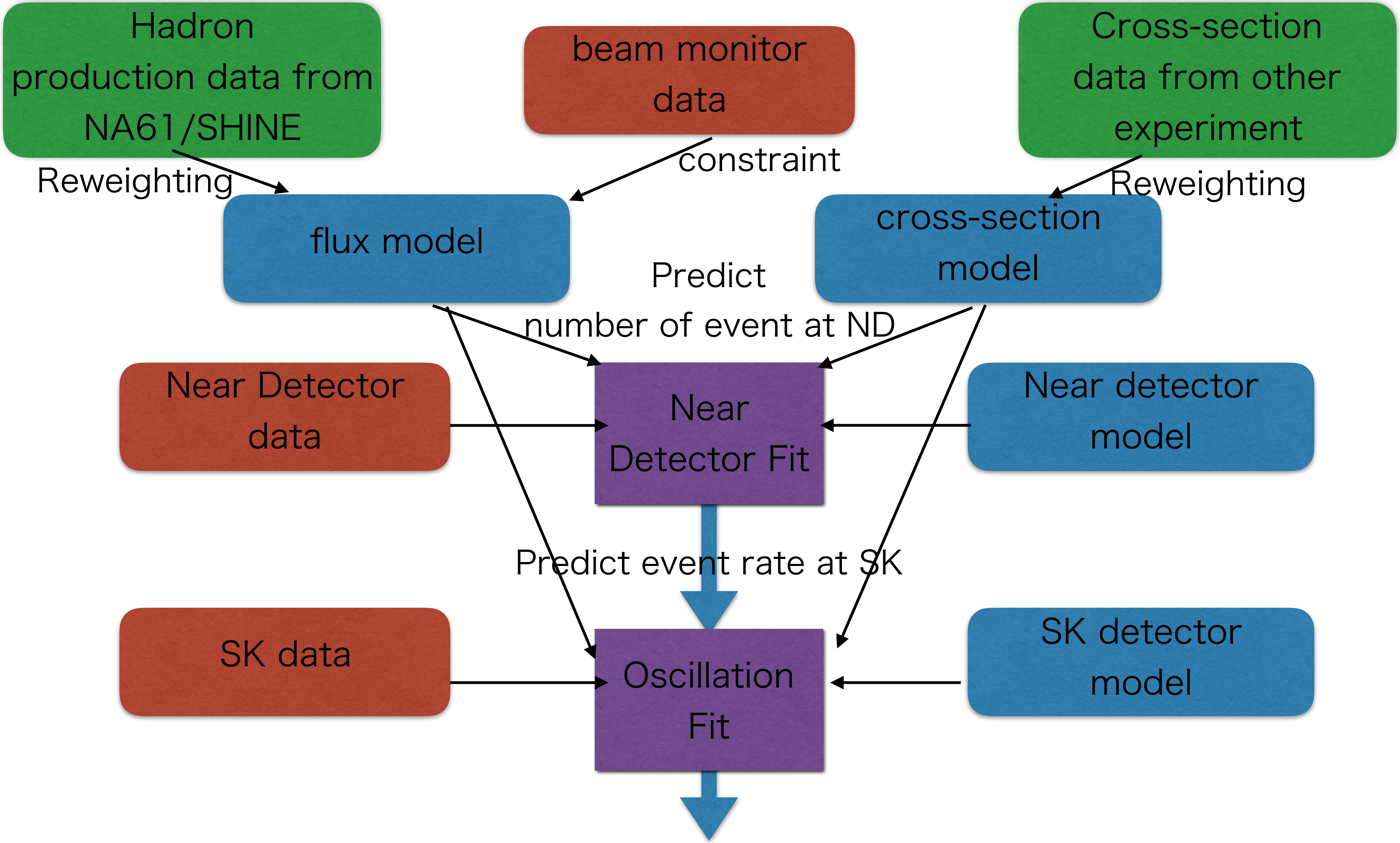
- The spectrum can be distorted by
  - pion production mode, which is absorbed inside the nucleus/detector.
  - Nucleon-Nucleon correlation inside the nucleus.
  - Fermi momentum, boundary energy…





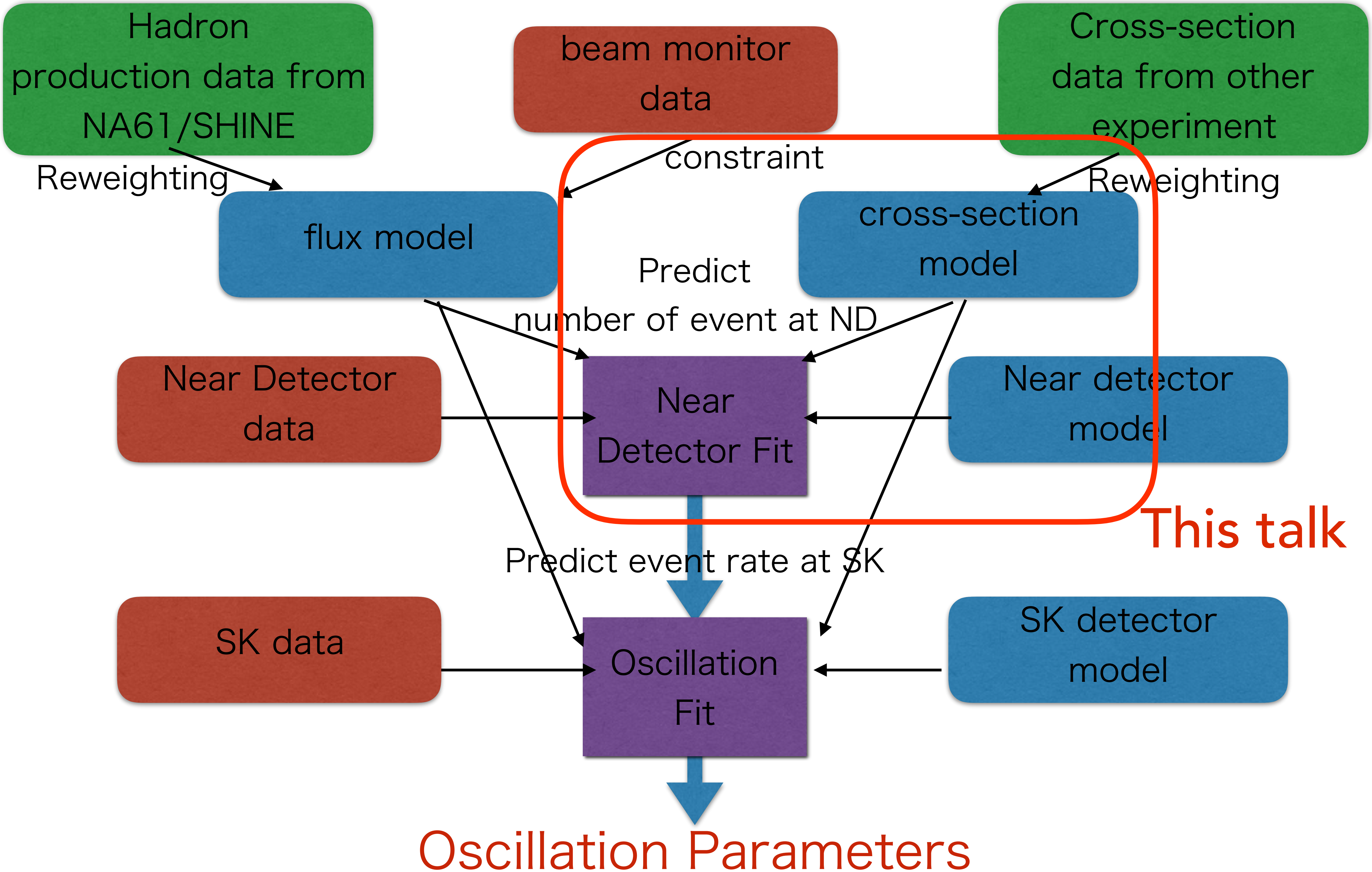
Precise understanding of neutrino interaction model is essential for Oscillation Analysis!

T2K Oscillation analysis strategy



Oscillation Parameters

T2K Oscillation analysis strategy



Cross-section model for 2017 Oscillation analysis

- We used 22 neutrino cross-section parameters in 2016.
- We have 31 neutrino cross-section parameters in 2017.
  - 13 parameters for CCQE-like samples
  - 3 parameters for CC single pion samples
  - 9 parameters for CC Other and other mode.
  - 6 parameters for Final State Interaction (FSI)

Cross-section parametrization (CCQE-like)

- MAQE: Axial mass
  - dipole form factor is used.

$$F_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^{QE\,2})^2}$$

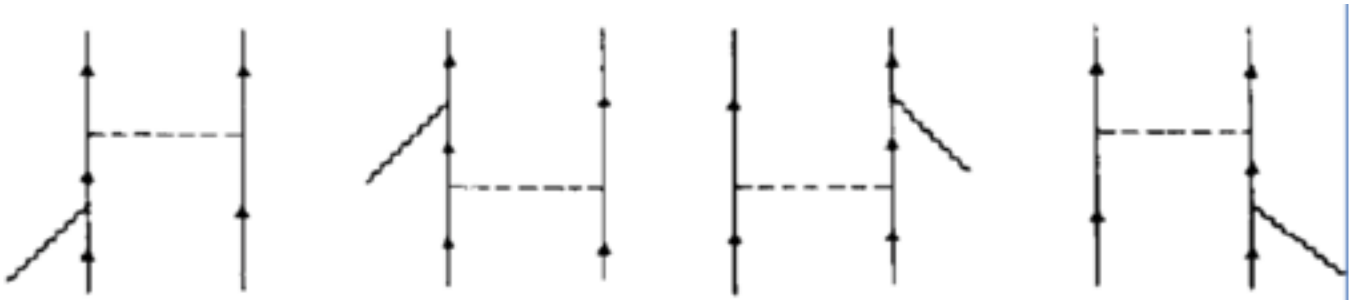
- Binding energy:found reweighting not working correctly.
  - not used in the fit
  - Will check the effects on oscillation analysis
- Fermi momentum of C and O.
- 5 parameters for multi-nucleon effects (2p2h) new!
- 5 parameters for Random Phase Approximation (RPA) model new!

2p2h=2 particle 2 hole

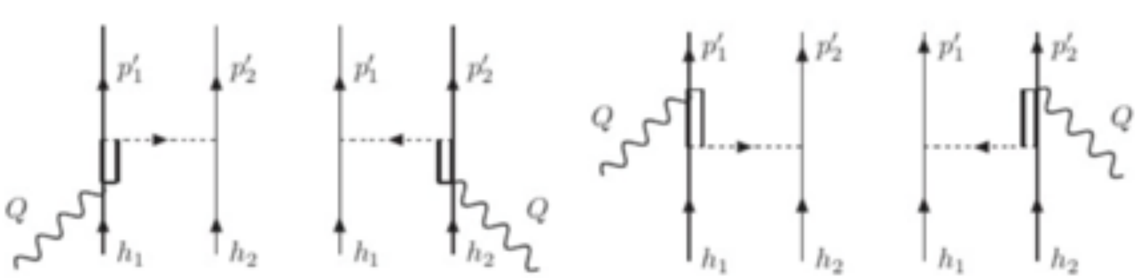
Multi-nucleon effects (2p2h)parameters

- Interaction in which more than one nucleon participate.
- Pion-less Delta Decay (PDD-like) and N-N Correlation (non-PDD-like)
- Introduced shape parameters in addition to normalization
  - +1 corresponds to fully PDD-like
  - -1 corresponds to fully non-PDD-like

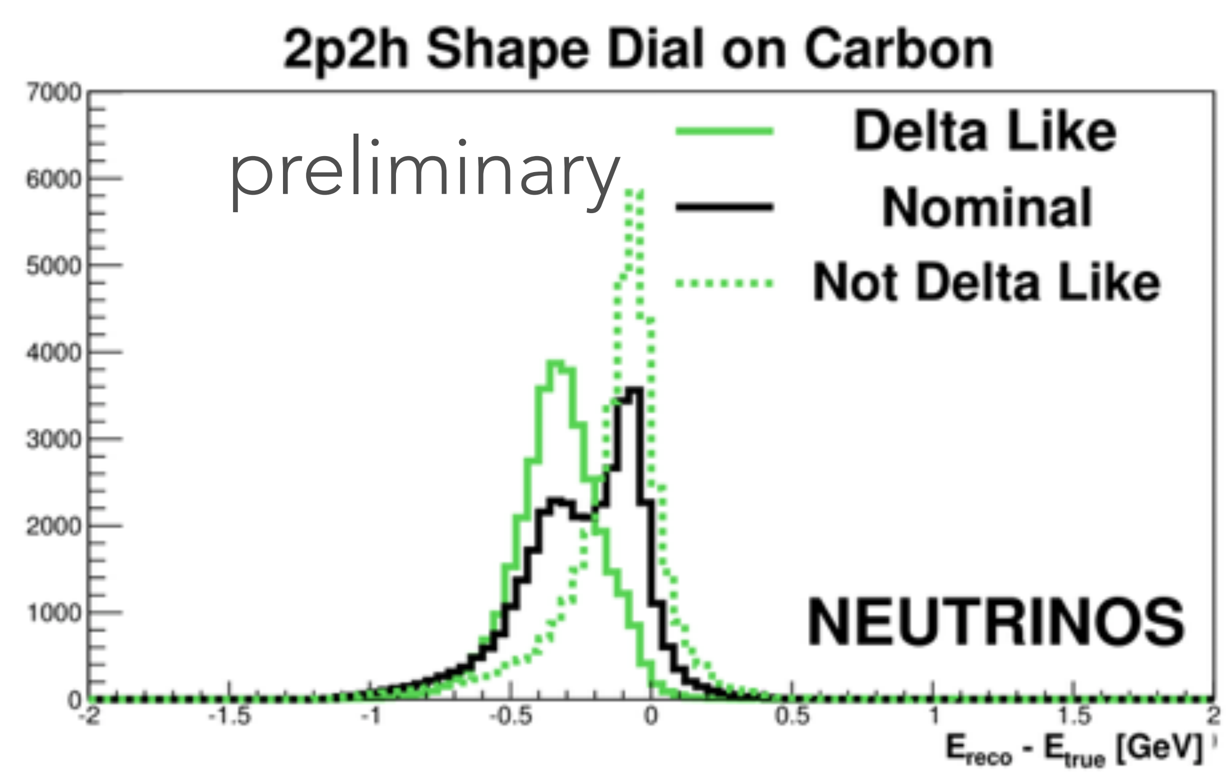
Pair Correlation



Delta absorption



Coupling to a Δ-resonance (Δ-pole)



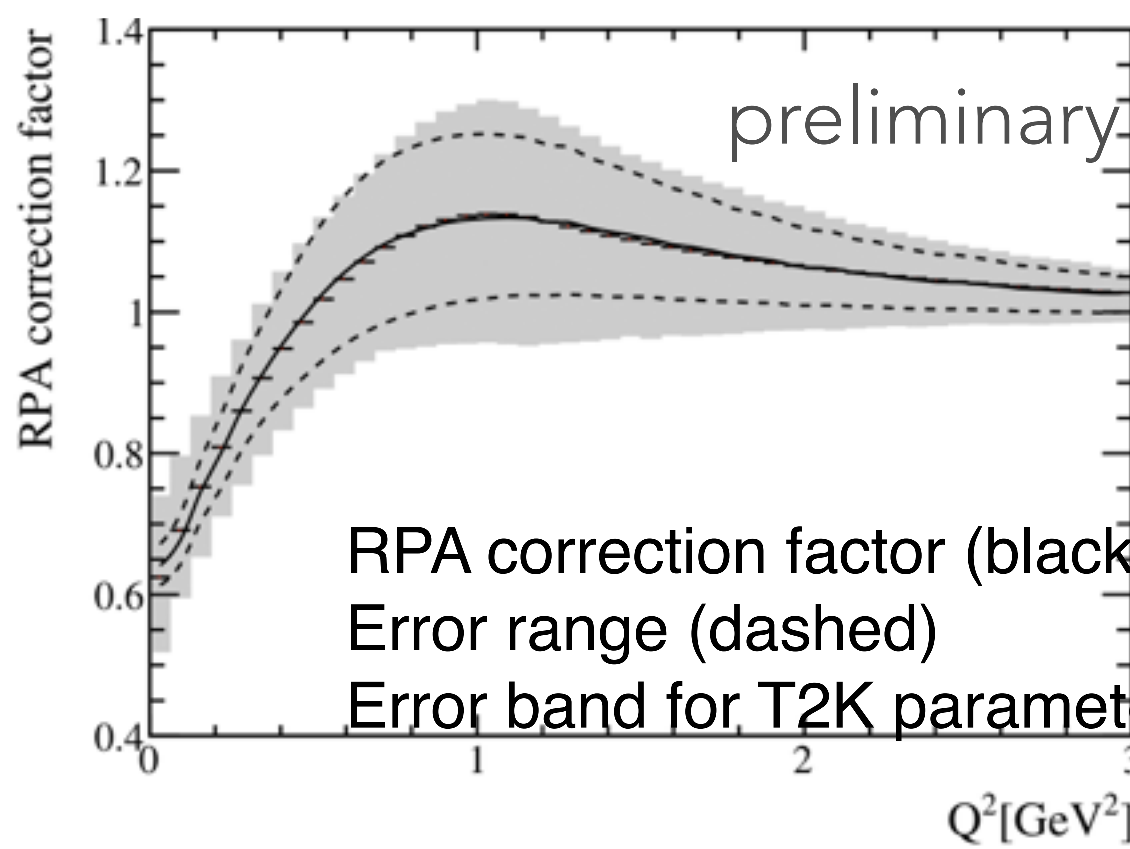
New Random Phase Approximation (RPA) model

- Long-range nuclear effects
- Introduced RPA in the fit as effective parameters
- Introduced new parameters based on Bernstein polynomials.

$$f(x) = \begin{cases} A(1-x')^3 + 3B(1-x')^2x' + 3p_1(1-x')x'^2 + Cx'^3, & x < U \\ 1 + p_2\exp(-D(x-U)), & x > U \end{cases}$$

x' = Q²/U

Uncertainties on the parameters cover the theoretical uncertainty on the RPA correction factor

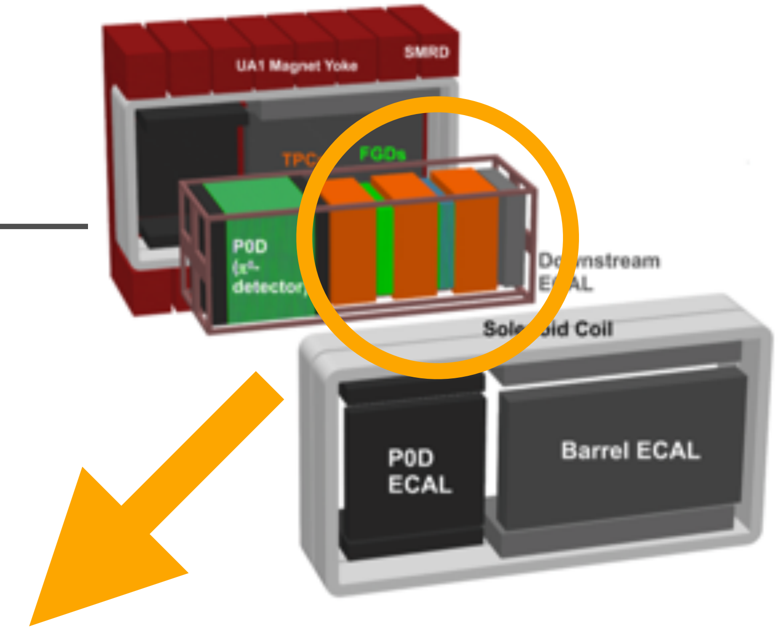


RPA correction factor (black)
Error range (dashed)
Error band for T2K parameters (gray)

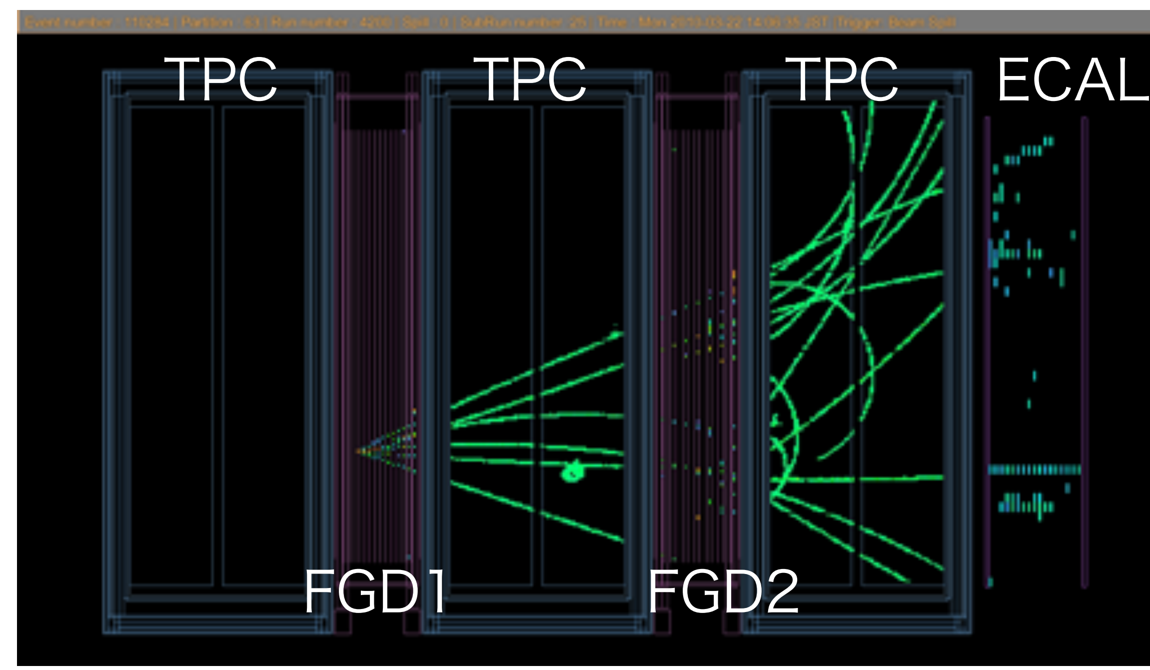
Cross-section parametrization(CC1π)

- Based on Rein-Sehgal model
  - MARES: Axial mass.
  - CA5: Axial form factor value at $Q^2=0$
  - background: Isospin 1/2 non-resonant background
- Re-tuning using bubble chamber data. new!

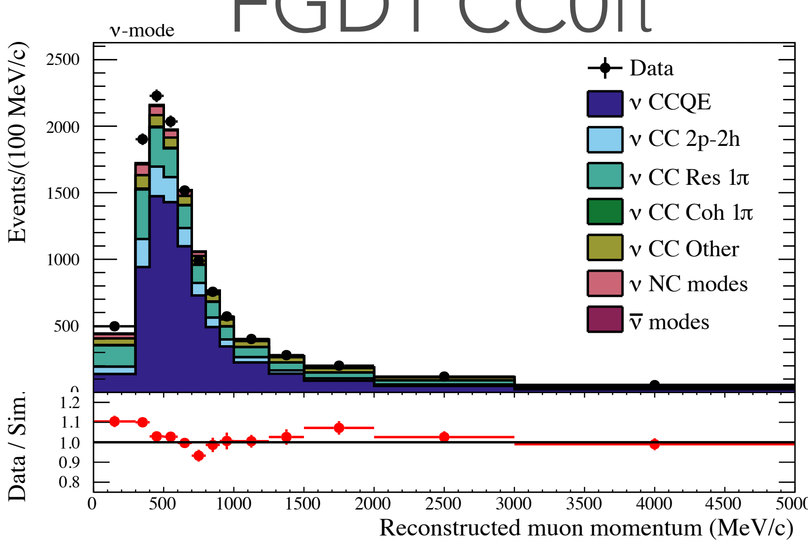
Near detector fit



- Fit to data to constrain cross-section model and flux parameters
- separated by number of charged pions for neutrino mode(CC0π CC1π CCOther)
- Different separation for anti- neutrino mode (CC1Track, CCNtrack)
- Separate data sets in FGD1 and FGD2 (water targets)

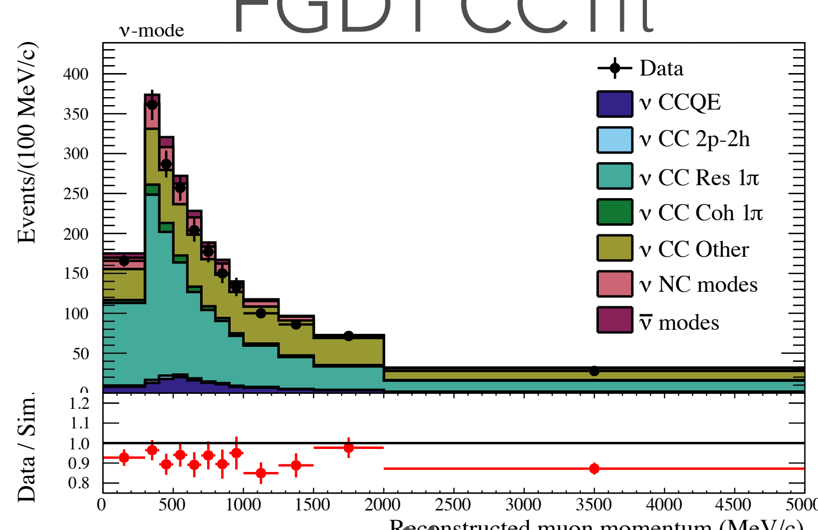


FGD1 CC0π



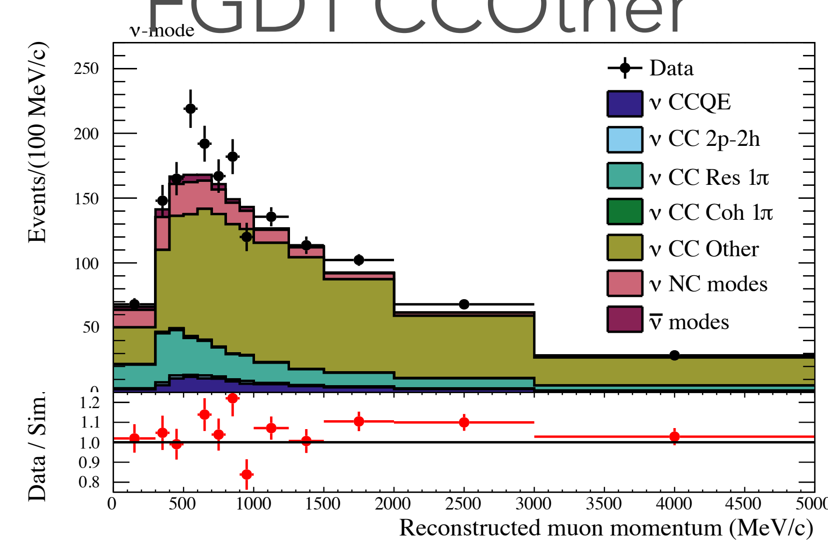
PRELIMINARY

FGD1 CC1π



PRELIMINARY

FGD1 CCOther



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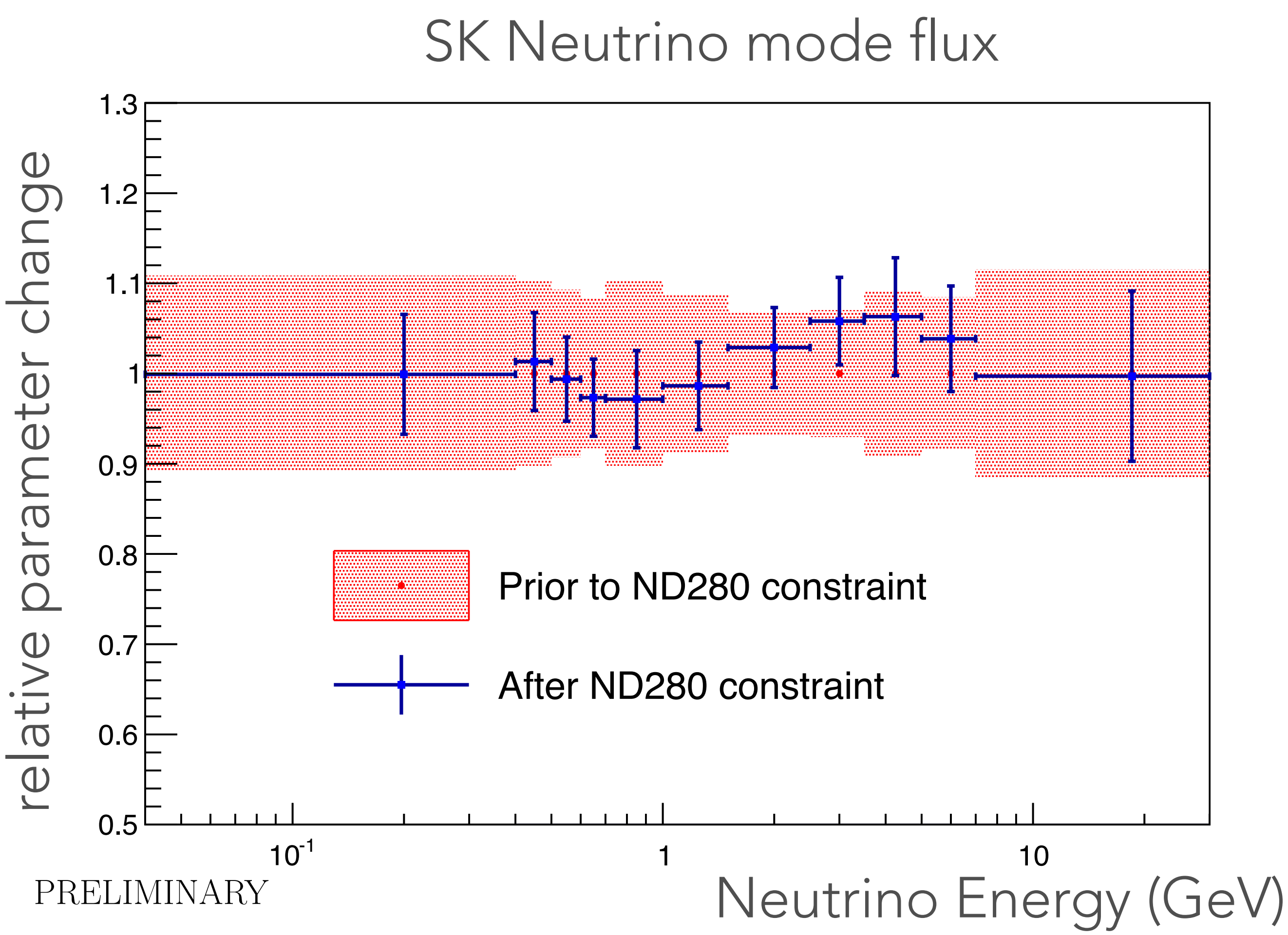
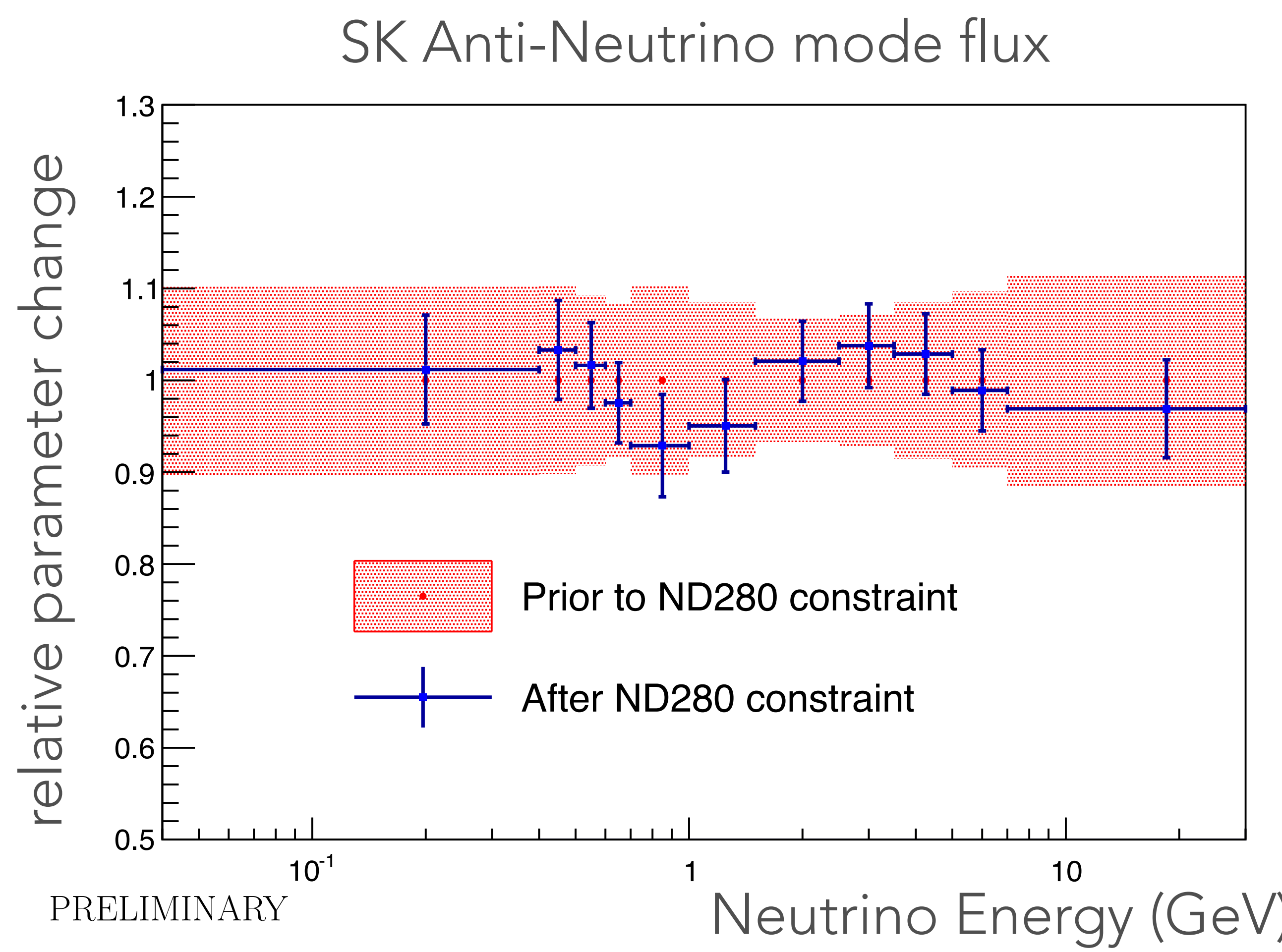
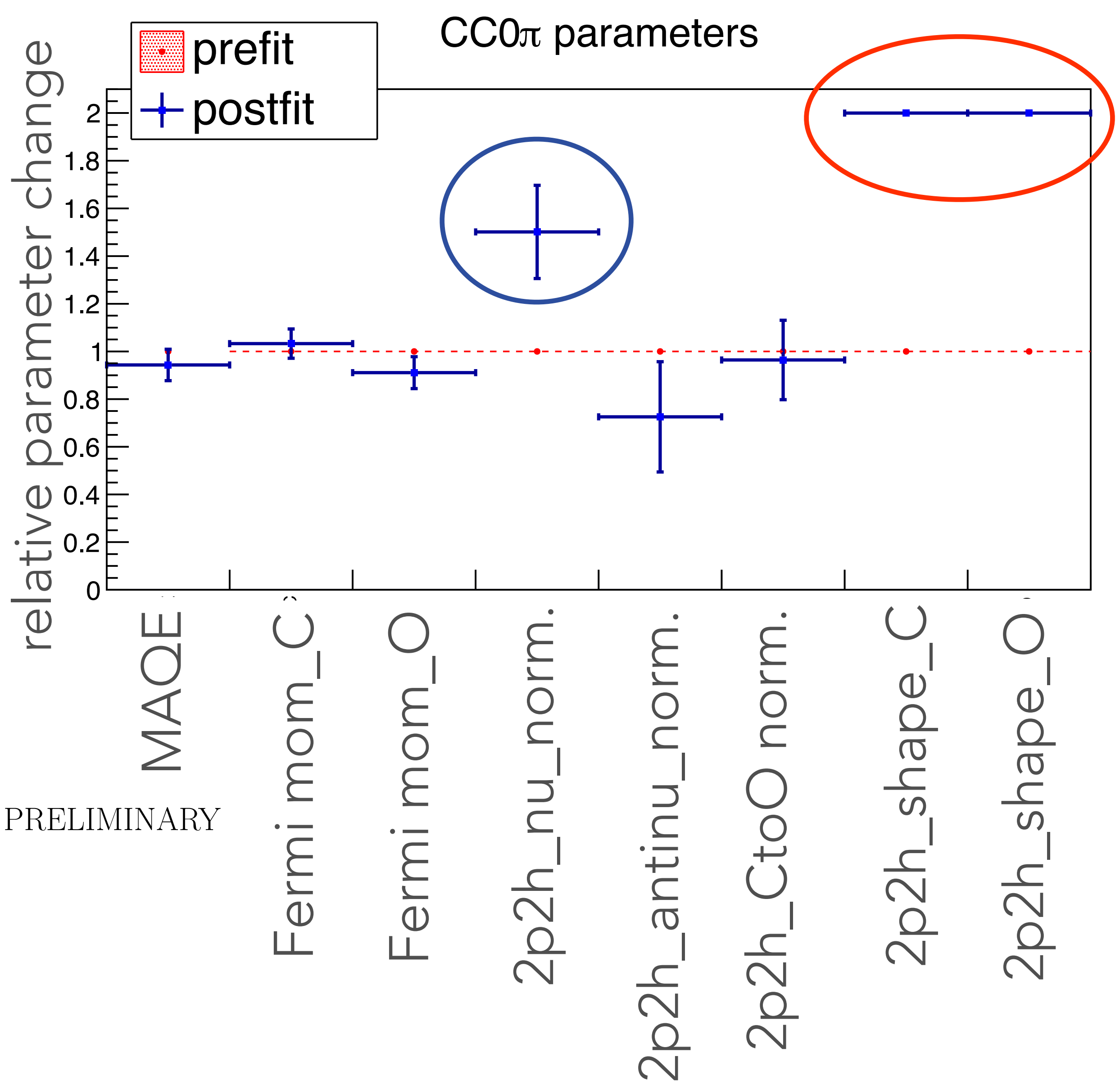
Near detector fit results

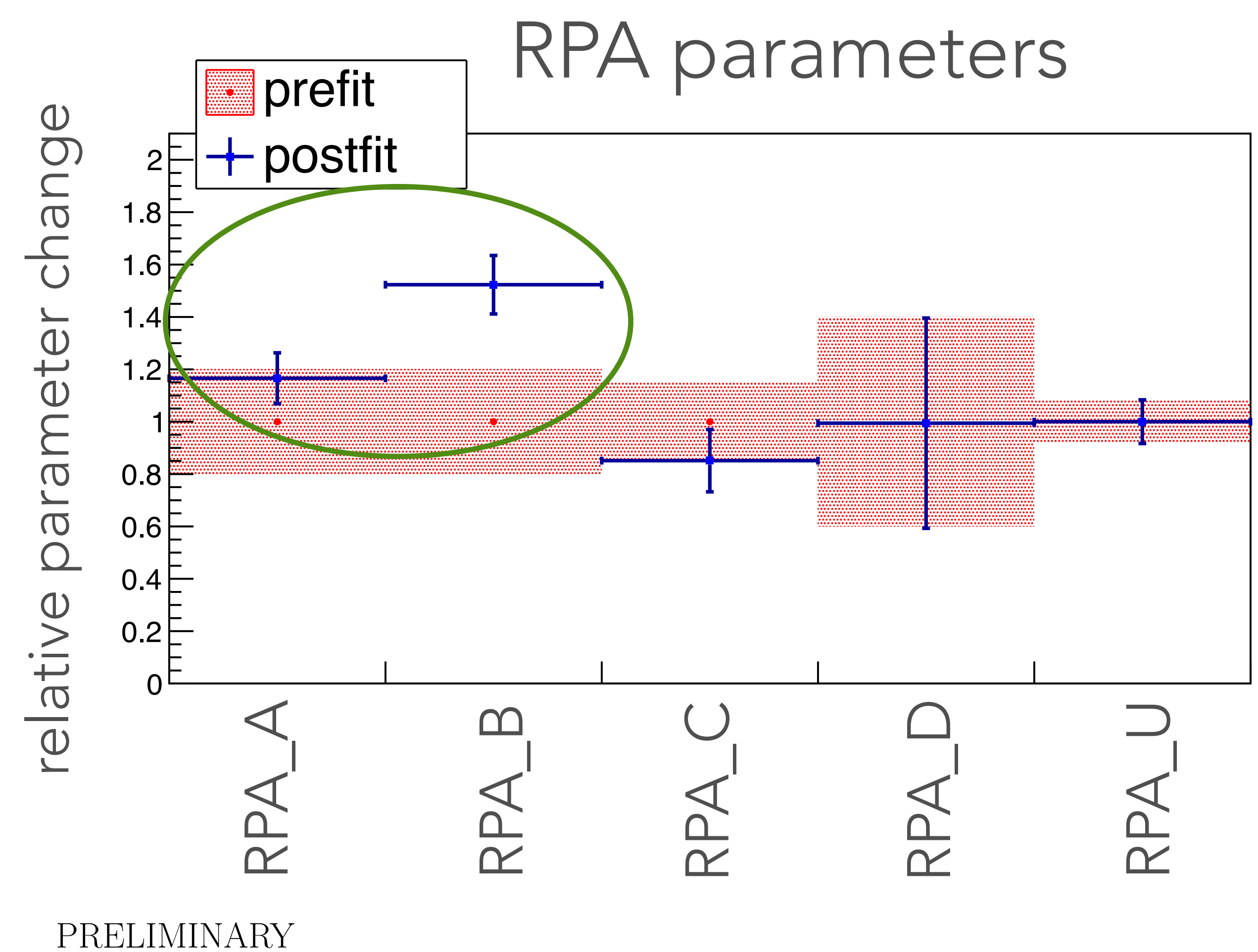




- Flux parameters stay around nominal.
  - Good agreement compared to 2016 results

Near detector fit results



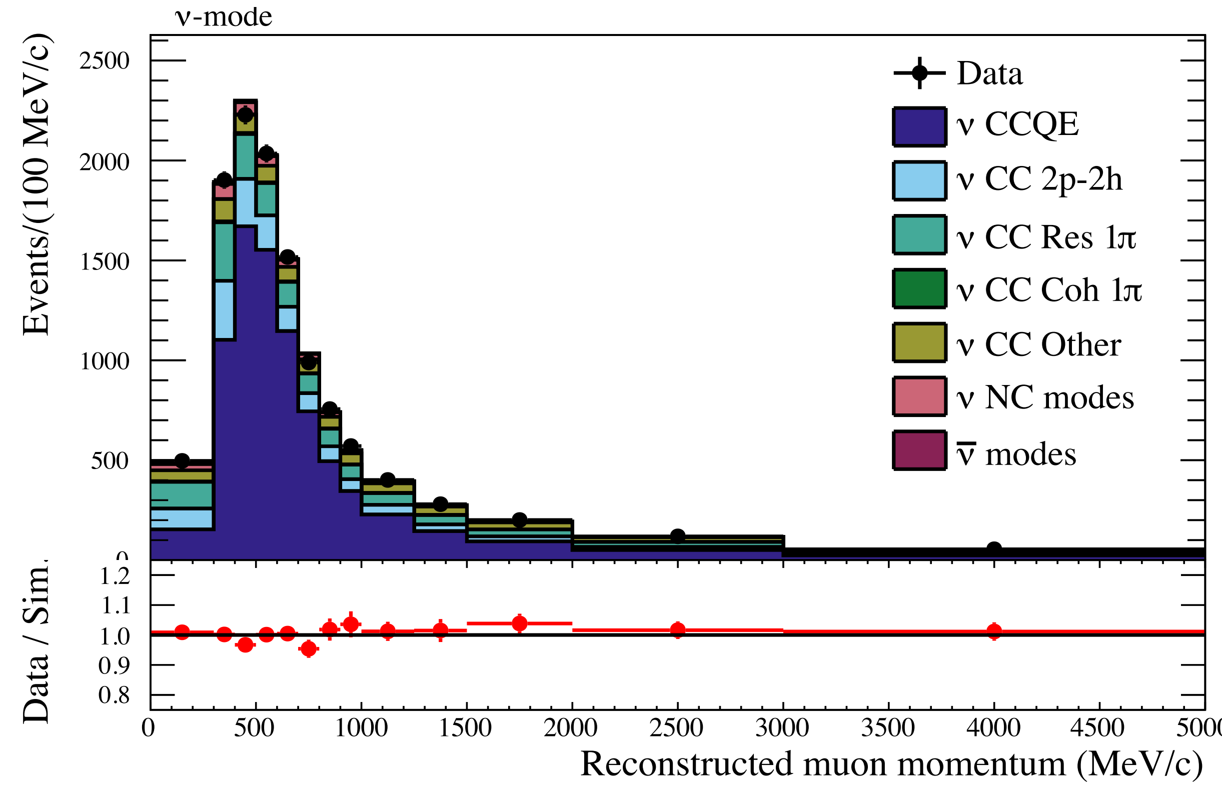


These results should not be taken as the cross section results, but effective parameters which effectively describe the data and propagate the uncertainty to the oscillation analysis.

Near detector fit results

- The fit reproduces the data well with a p-value of 0.47 (0.08 in 2016)
    - Thanks to more degrees of freedom by adding new RPA parameters
- Flux + cross-section uncertainties at SK ~3.22% for (e-like and μ-like)

FGD1 CC0π



PRELIMINARY

The latest oscillation fit results are shown in the Patrick's (Sep. 27th) and Jiae's (Sep. 26th) talk

The latest cross-section measurements are shown in the Ciro's (Sep. 25th) talk.

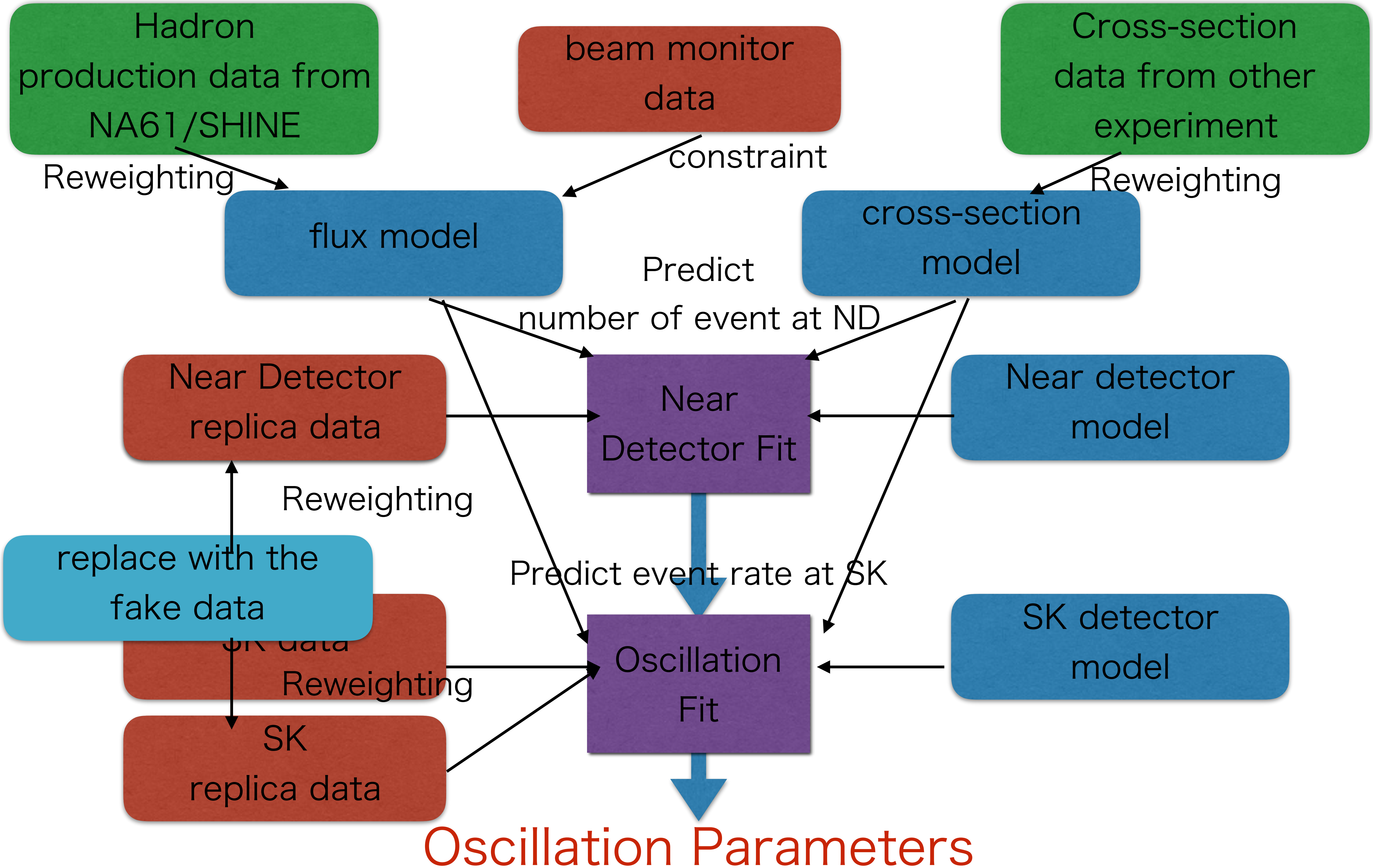
Effects of different models on oscillation analysis

- Check the robustness of the fit against neutrino interaction modeling
  - The choice of interaction model
  - Alternative model which is not included in the MC
- Interaction model which cannot be covered by current model may introduce spectrum distortion at far detector and effects to oscillation parameters

Fitting "fake datasets" at Near/Far detector to evaluate biases on the oscillation parameters, due to the choice of interaction model

"fake datasets"=simulated data set by alternate model

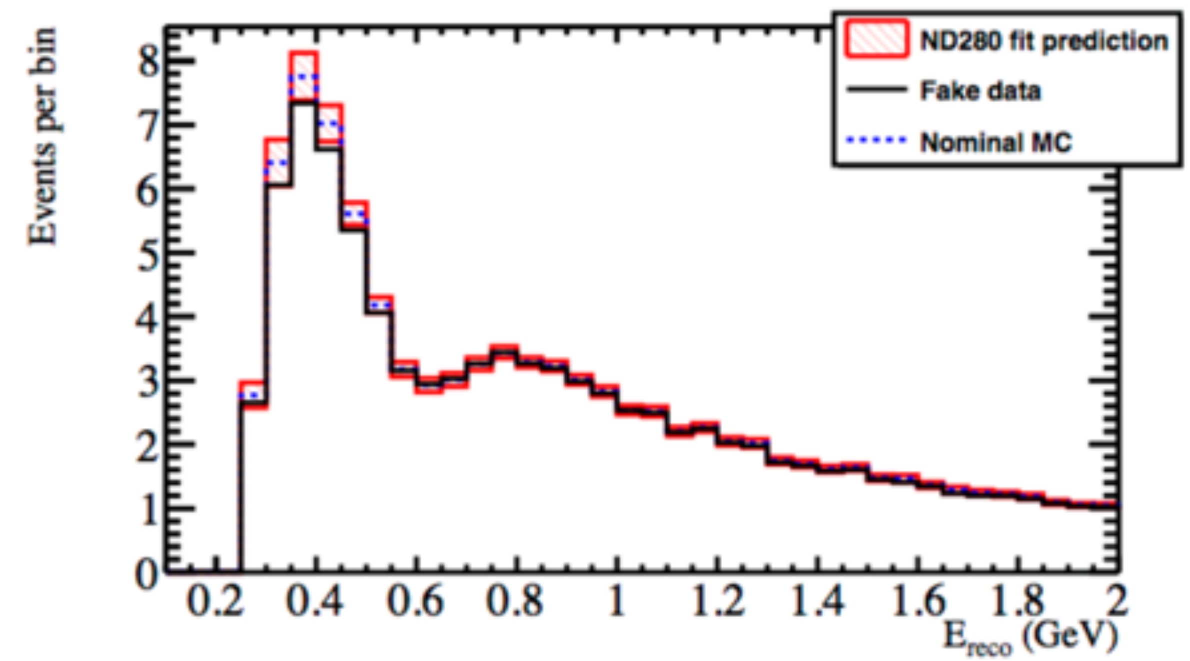
Fake data fitting



Interaction models studied using 2016 framework

- Martini 2p2h model
- Spectral Function
- effective RPA model
- Nieves vs NEUT model difference

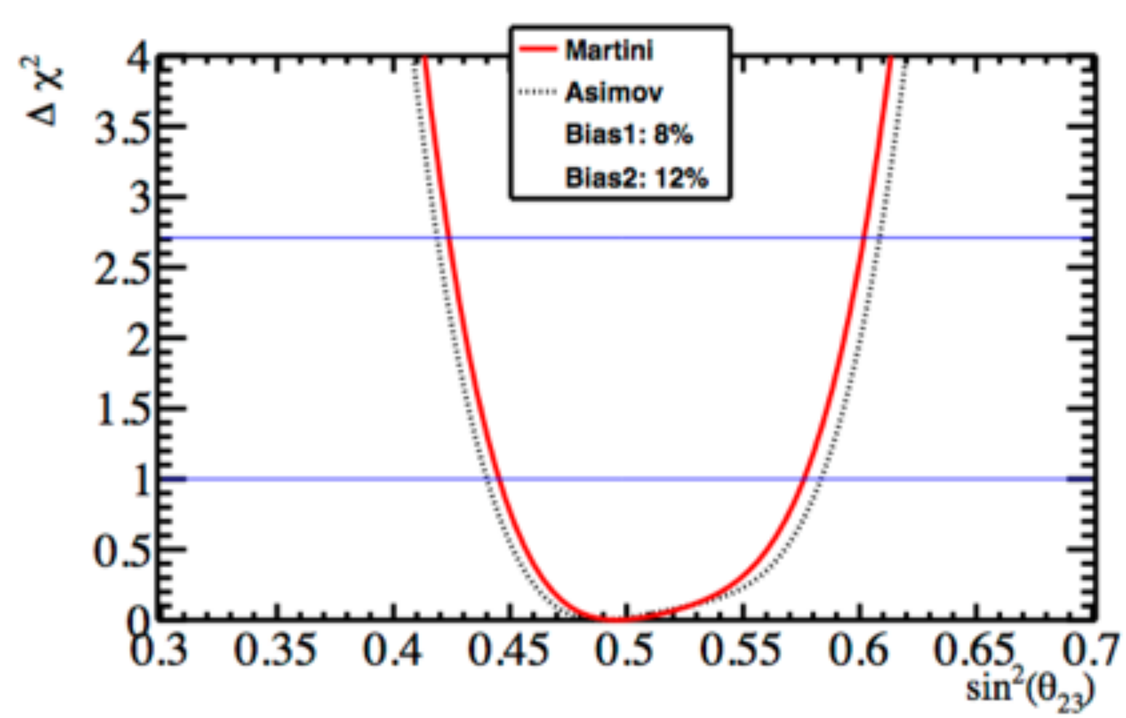
μ like Spectrum at SK (Martini)



Bias definition

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

$\sin^2\theta_{23}$sensitivity (Martini)



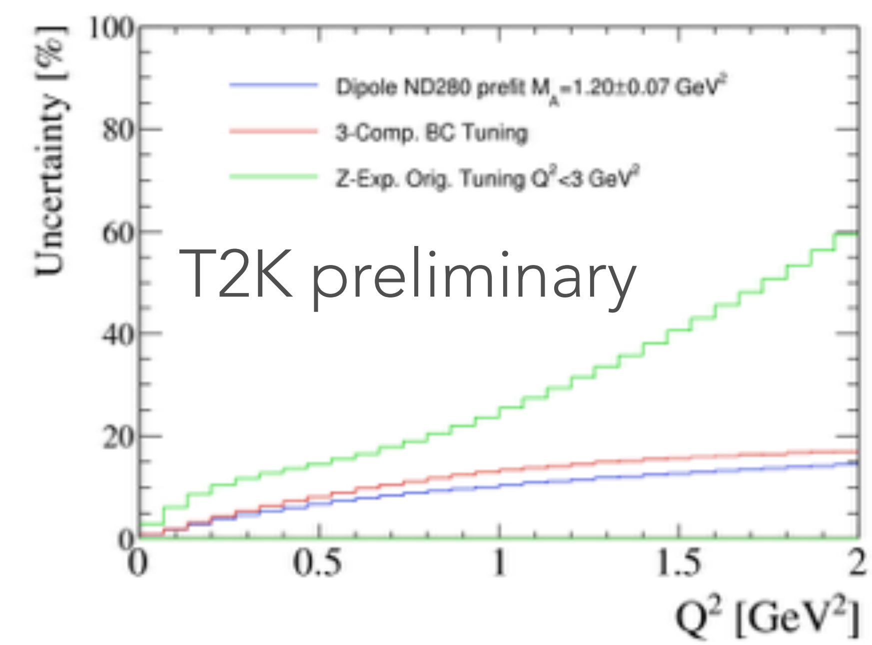
Absolute bias on the $\sin^2\theta_{23}$ parameters

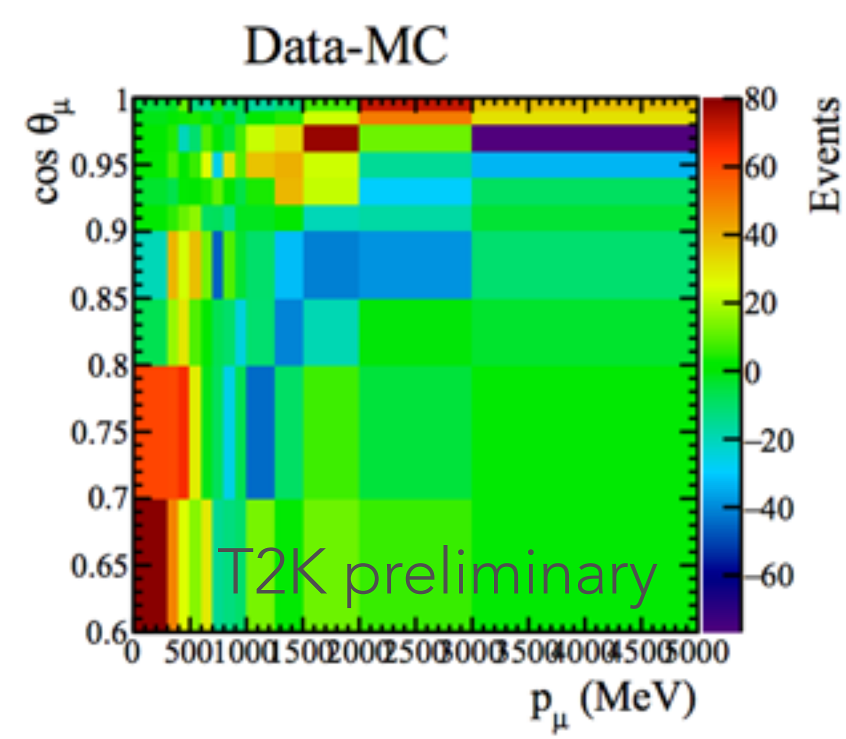
~0.2σ for the model above

Prospects for 2017 framework

- Proposed cross-section model
  - Alternative model for form factor
  - Improved CC single pion model
  - Improved Pion Multiplicity tuning
  - Binding energy effects
- Data-driven fake data
  - Data-MC difference at Near Detector
    - Assigned to
      - 1p1h
      - 2p2h Delta-like
      - 2p2h non-Delta-like
    - Checked that the effects on δ_{CP} is negligible, Study is on-going for $\sin^2\theta_{23}$ vs Δm^2_{23}
  - Minerva data-driven fake data

Error size of each form factor model





Summary

- T2K has been developing new interaction modeling for oscillation analysis in 2017.
  - The near detector fit reproduce the data well with a p-value of 0.47.
- We have performed “fake” data study to investigate the robustness against various cross-section models for oscillation analysis.
- We are pursuing to do various “fake” data studies with 2017 framework.

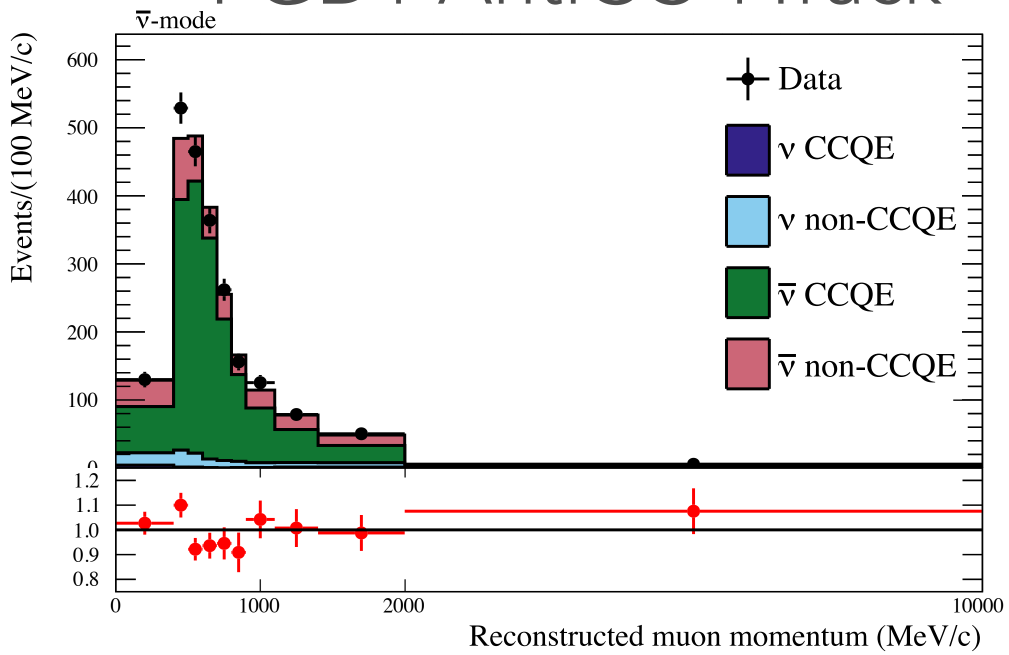
Reference

- J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas. Inclusive Charged–Current Neutrino–Nucleus Reactions. Phys. Rev., C83:045501, 2011.
- L.M. Sehgal D. Rein. Neutrino-Excitation of Baryon Resonances and Single Pion Production. Annals of Physics, 133:79–153, 1981.
- C. Adamuscin, E. Tomasi-Gustafsson, E. Santopinto, and R. Bijker. Two-component model for the axial form factor of the nucleon. Phys. Rev., C78:035201, 2008.
- Bhubanjyoti Bhattacharya, Richard J. Hill, and Gil Paz. Model independent determination of the axial mass parameter in quasielastic neutrino-nucleon scattering. Phys. Rev., D84:073006, 2011.
- M. Martini, M. Ericson, G. Chanfray, and J. Marteau. A Unified approach for nucleon knock-out, coherent and incoherent pion production in neutrino interactions with nuclei. Phys. Rev., C80:065501, 2009.

Backup

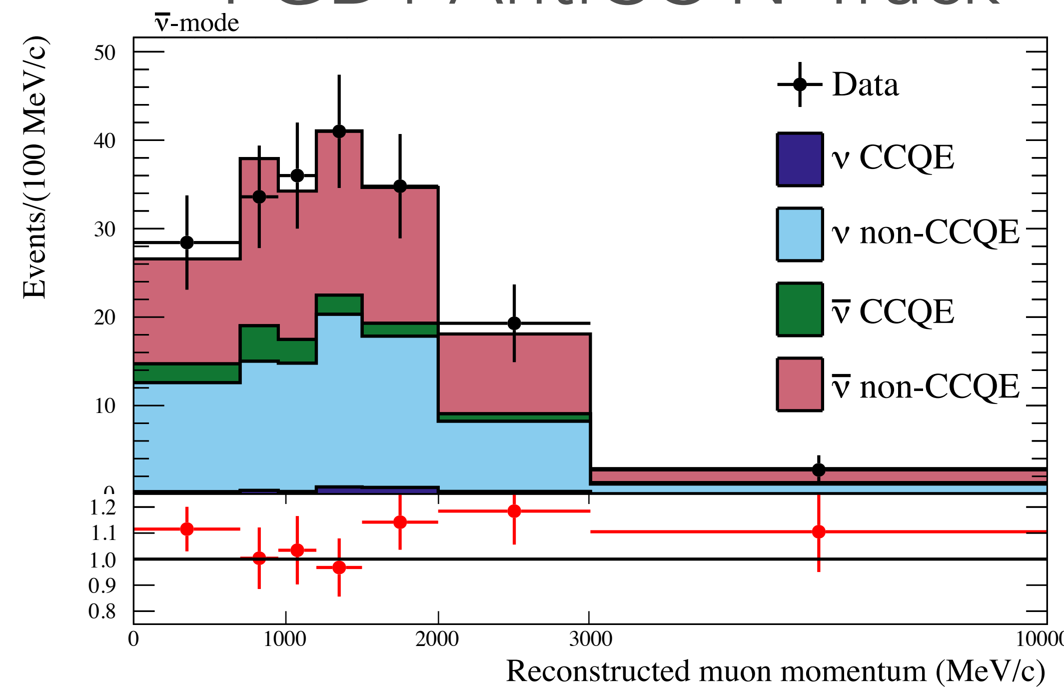
anti-neutrino mode events

FGD1 AntiCC 1Track



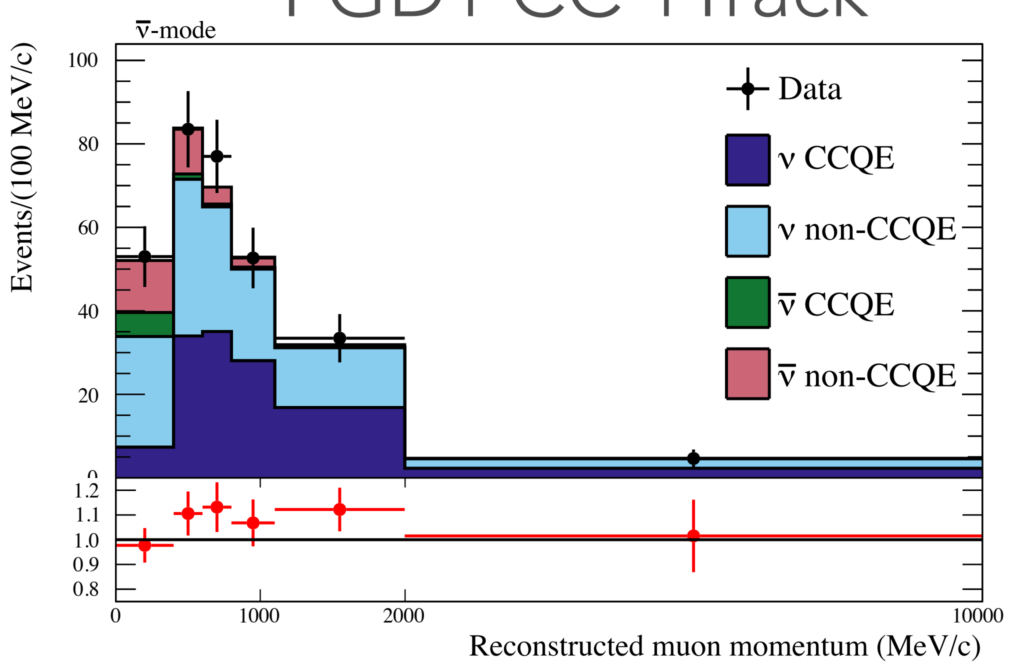
PRELIMINARY

FGD1 AntiCC N-Track



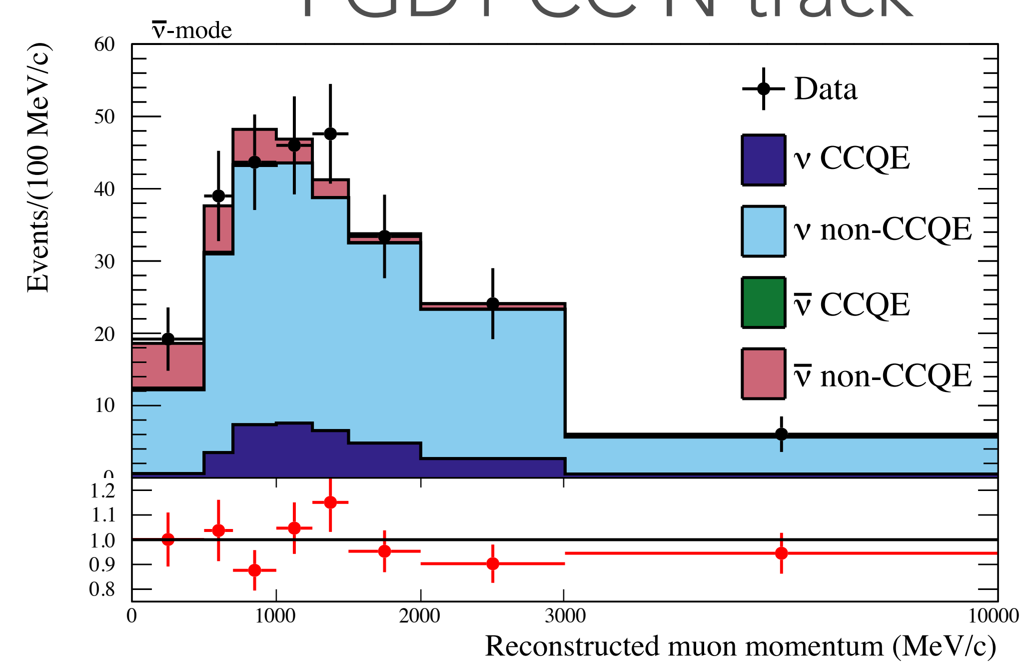
PRELIMINARY

FGD1 CC 1Track



PRELIMINARY

FGD1 CC N track



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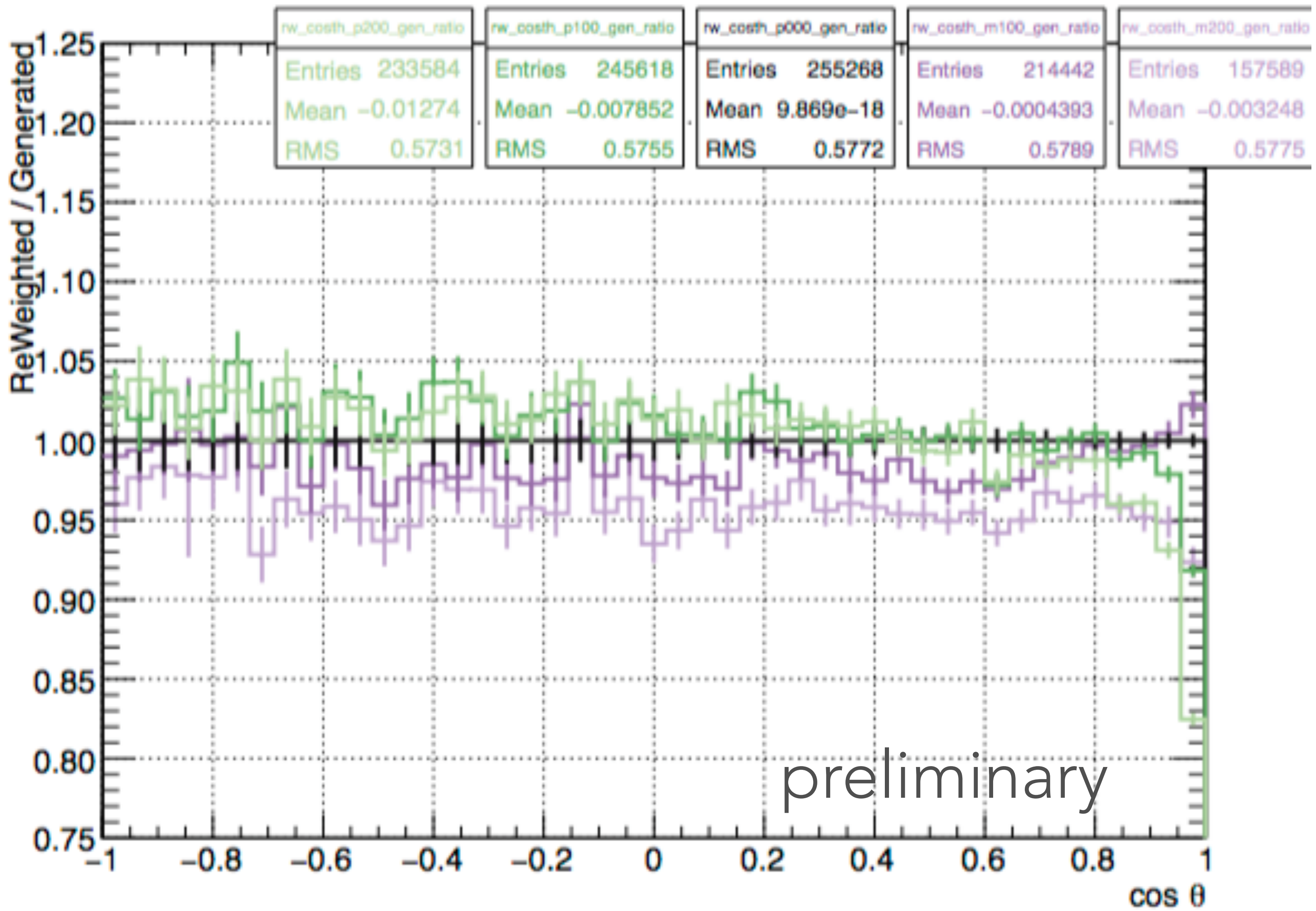
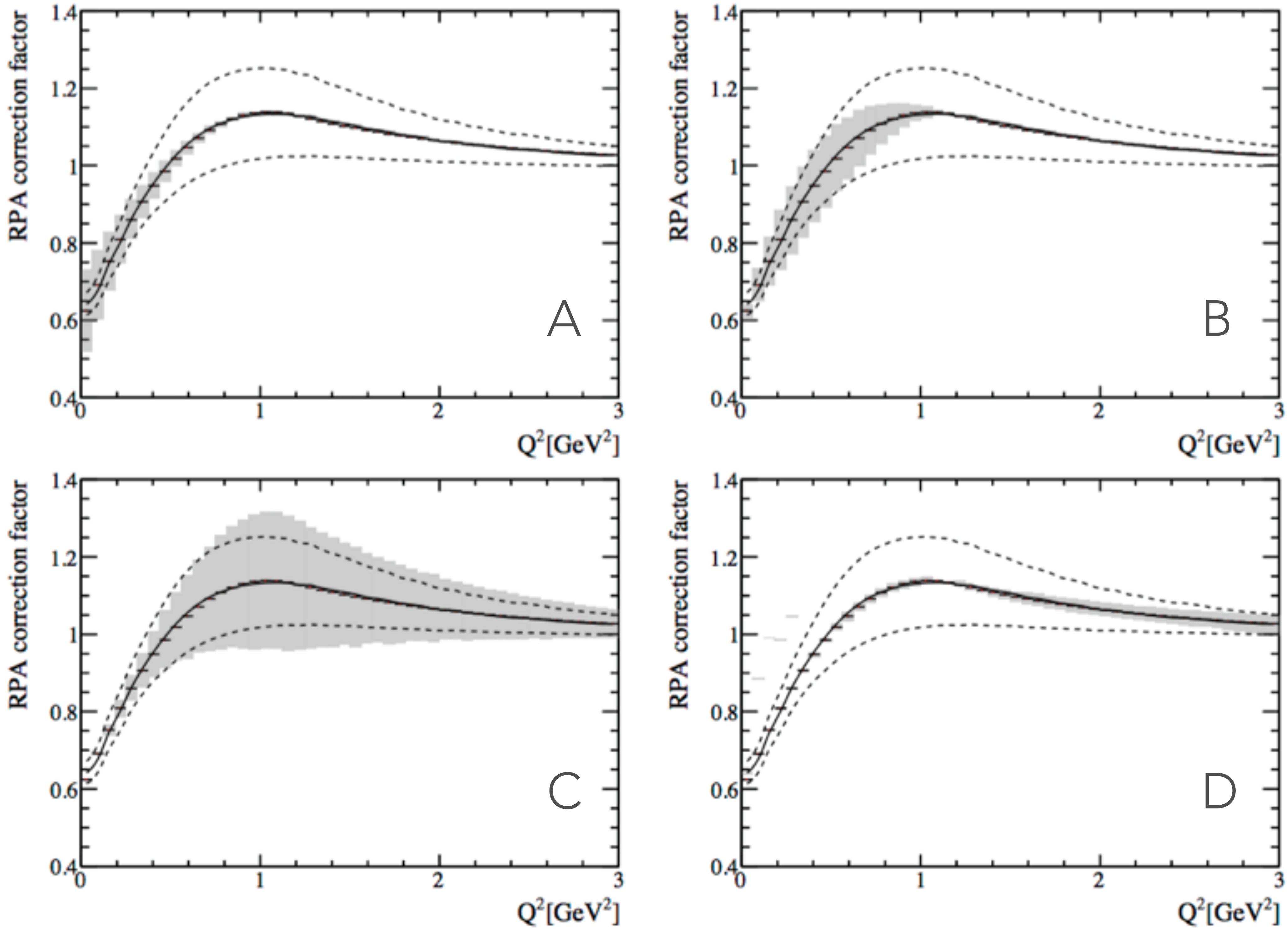
binding energy



- The bias of various binding energy.

Bernstein RPA model



IMPACT ON ATMOSPHERIC PARAMETERS

- In this study, Δm^2_{32} is biased to lower values
- $\sin^2\theta_{23}$ is biased towards maximal disappearance
  - Leads to narrower contour than fit to nominal prediction
- Shift towards maximal also seen in 1-D contour for oscillation parameter set B (bottom)