Systematic Errors for FiTQun Analyses

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SK Detector Error Strategy

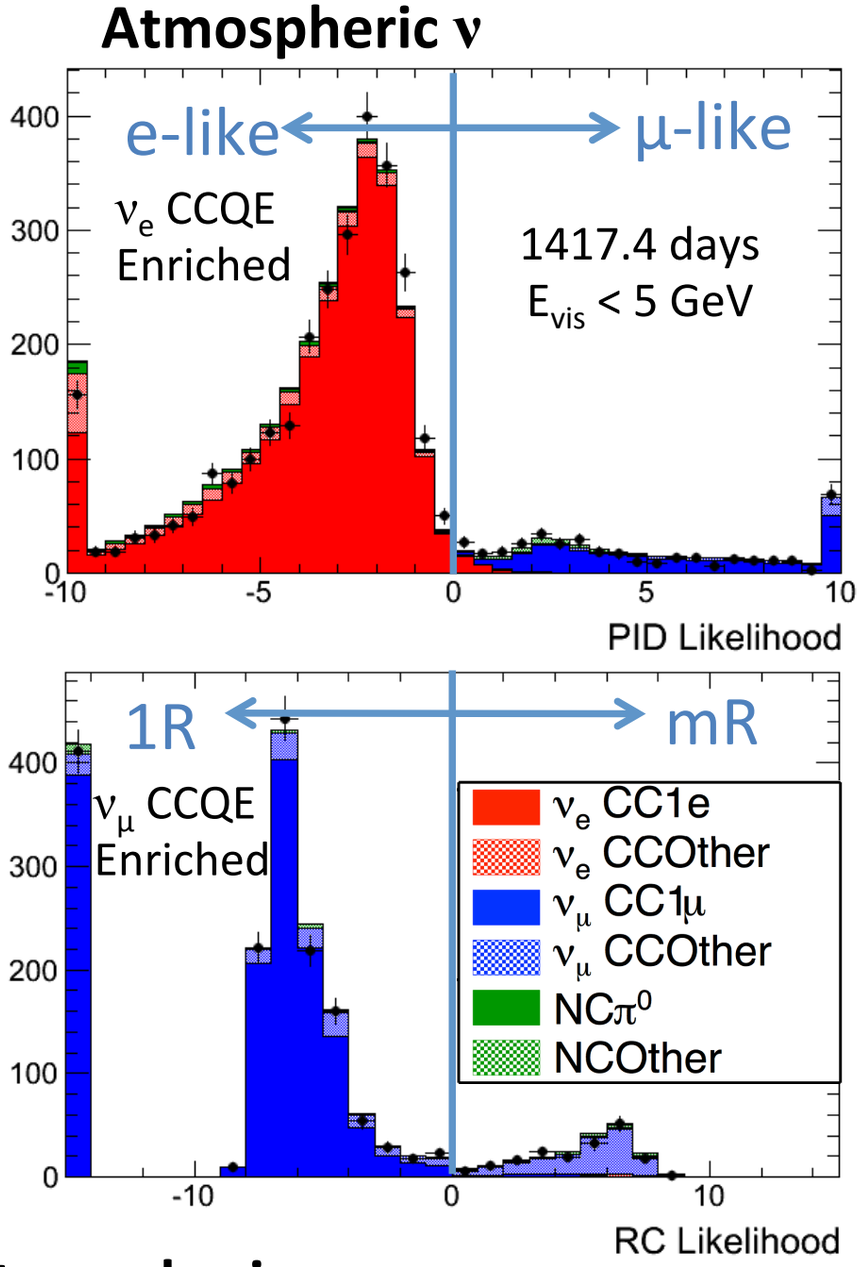
- The current detector systematic errors are largely set using a fit to atmospheric data
  - This is problematic, since this strategy builds into the detector errors poorly understood flux and cross section
- In the longer term, we would like to move to a strategy that is based more on calibration and control samples
  - This may take a significant amount of time and effort
- However, the first fiTQun-based analyses hope to finish within the next year
- This suggests that we need to have a plan to address SK detector errors that still may have to include atmospheric data in the short term
  - **Important question**: is the current atm data fit sufficient for the analyses we want to perform int he short term?

SK Detector Error Requirements

- **All analyses**
  - FV determination and systematic errors (may be different for each analysis!)
- **T2K 1-ring ν_e and ν_μ analyses**
  - May be possible to use current atm fit framework
  - Some additional work may be needed for pion/muon separation cut
- **T2K 2/3-ring $CC\pi^+$ analyses**
  - Non-trivial extension to include multi-ring samples in the current atm fit would be needed
  - Would also likely need some sort of hybrid muon/pion control sample to study efficiency (possible to create?)
- **SK atmospheric and $p \rightarrow e^+ \pi^0$ analyses**
  - It seems very difficult to extend the T2K atm fit to multi-ring samples
  - Also, the detector errors and oscillation parameters would have to simultaneously be determined using a fit to the same dataset
  - Extensive use of hybrid samples may be required
- **$p \rightarrow e^+ \pi^0$ analyses**
  - May be the easiest, since these events contain mono-energetic muons and photons, and the hybrid technique is designed to test low energy + high energy ring configurations

Review of T2K-SK Detector Error Procedure

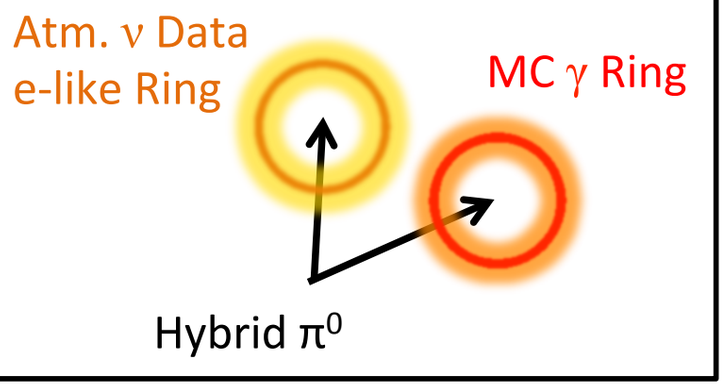
- Select very pure, relatively high statistics, samples in Atm-ν data with only 1e or 1μ in final state (FS)
- Effectively parameterize detector systematics with PID, RC and π^0 cut parameters (β)
  - Shifts the likelihood of a given event
- Constraints from cosmic μ and other background control samples
- Combine Atm-ν samples into a fit to extract data-MC discrepancies and propagate as systematic error on T2K prediction using toy MC



Stopping Cosmic μ

- Fiducial Volume ~ 1%
- Decay-e ~ 1%
- μ PID ~ 0.3%

Hybrid π^0 Samples



Atmospheric ν

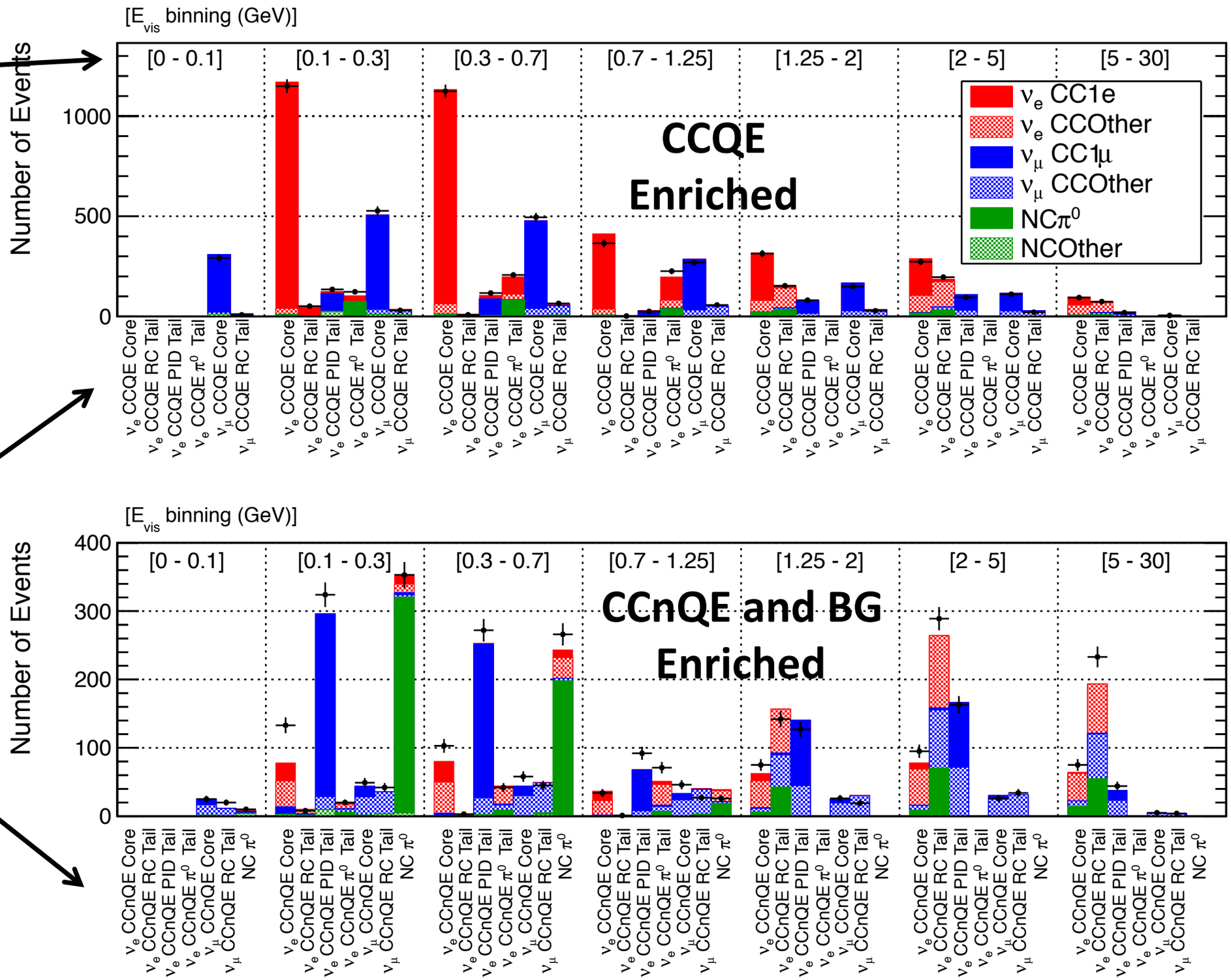
- Reduction ~ 1%
- *CCnQE enriched samples*
- *NC $1\pi^{\pm}$ and NC Other ~ 60-100%*

Atm-ν Control Samples

- Updated data set: 1417.4 to 1632.3 days livetime

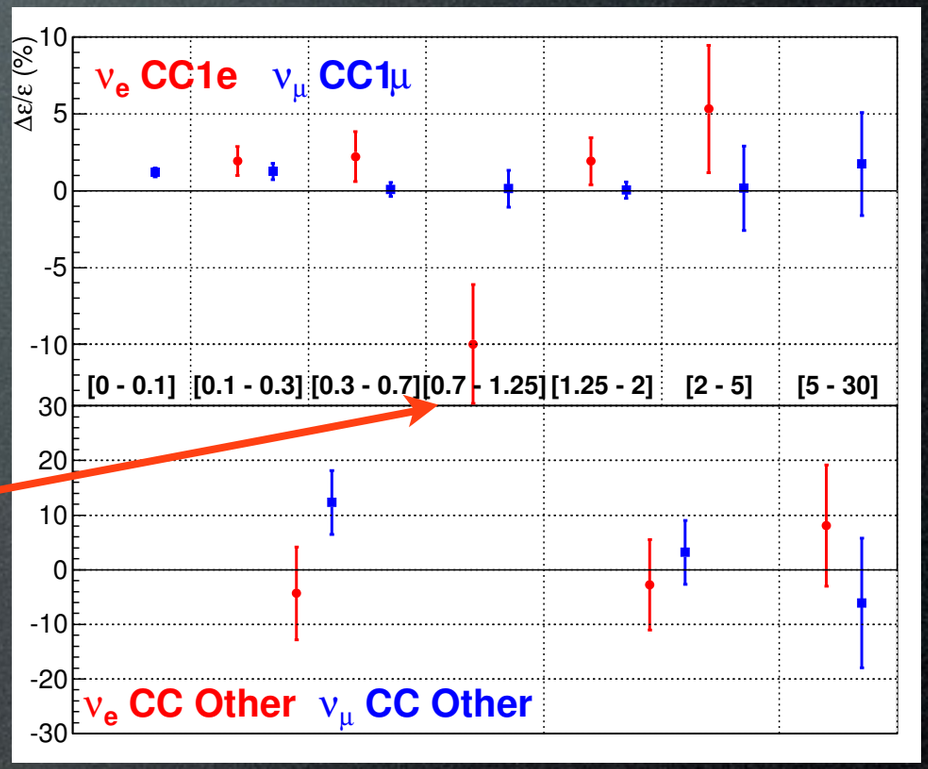
7 visible energy bins

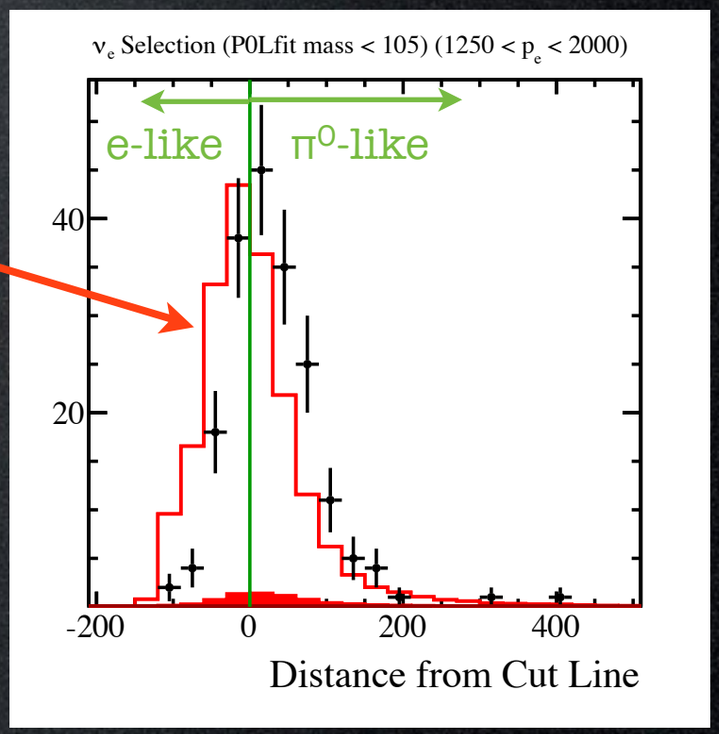
ν_e and ν_μ core and (RC, PID, π^0) tail samples



Fit Results

- Uncertainties are calculated in bins of visible energy
- Total detector error is a quadrature sum of:
  - "fit error": the error bar from the fit
  - "shift error": the deviation of the fit value from zero
- Large ν_e shift error seen in the 0.7-1.25 GeV bin
  - Above this energy, the π^0 cut is not used
  - Atmospheric 2-ring data looks more π^0-like than atmospheric MC
- To reduce error, must understand what detector mismodeling is responsible for the shift
  - Or perhaps modeling of the atmospheric flux or neutrino cross sections is the problem...





More Detail

At higher energies the data/MC discrepancies get larger

Note that the data look more pi0 like

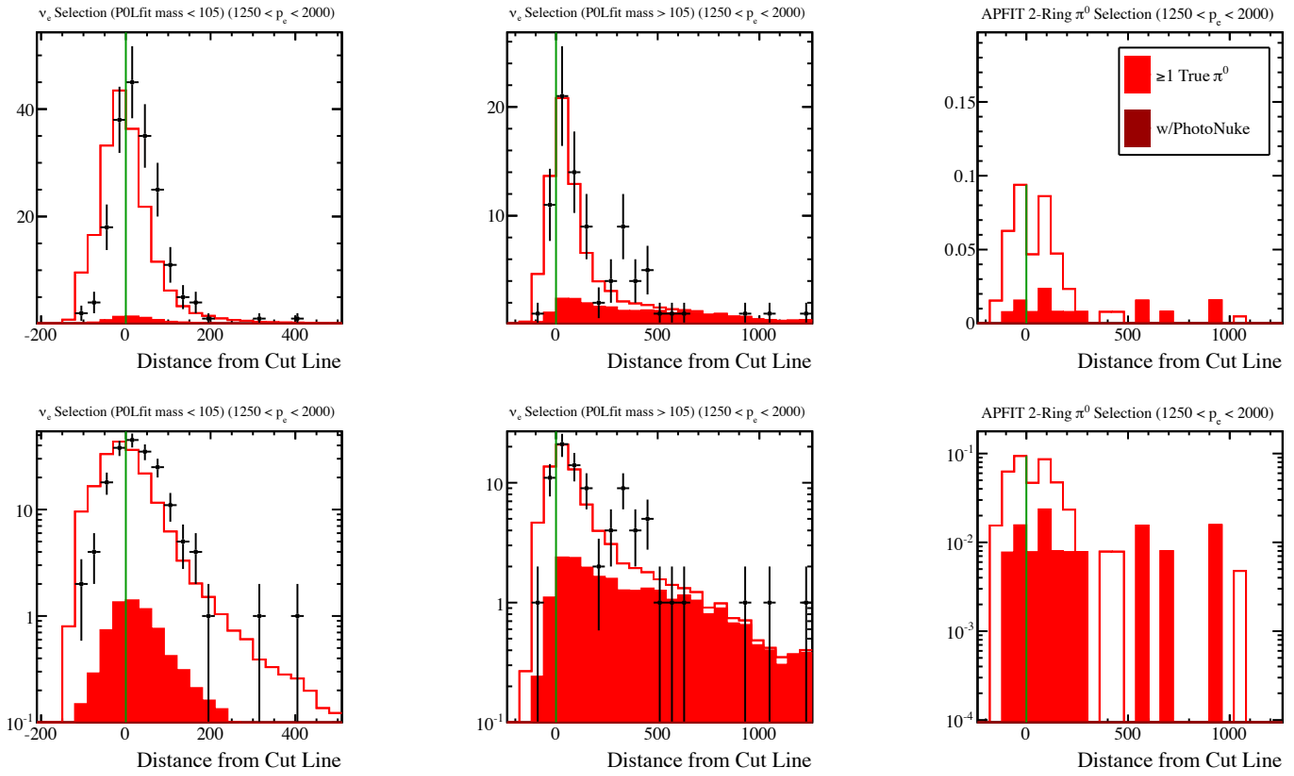


Figure 134: Distance from the T2K fiTQun π^0 rejection cut line for the APFIT selections as described in the text and $1250 < p_e < 2000$ MeV/c.

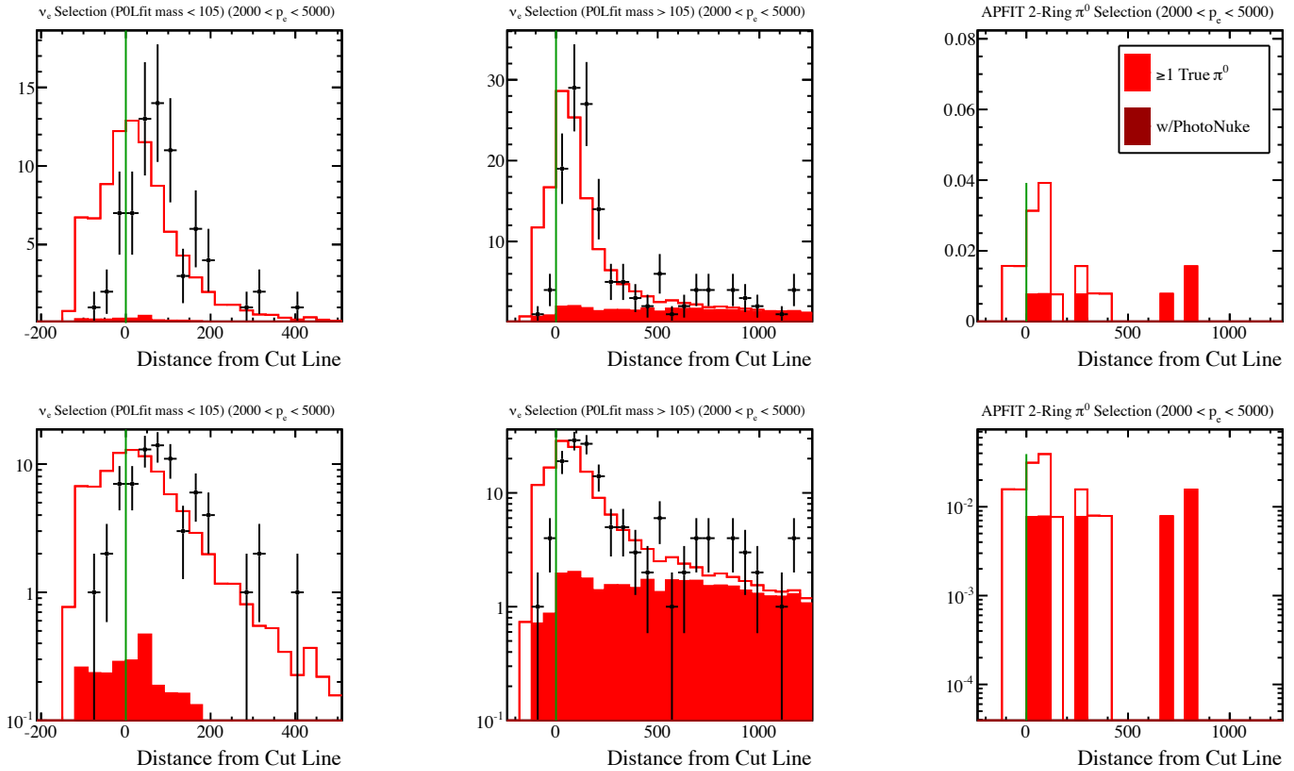
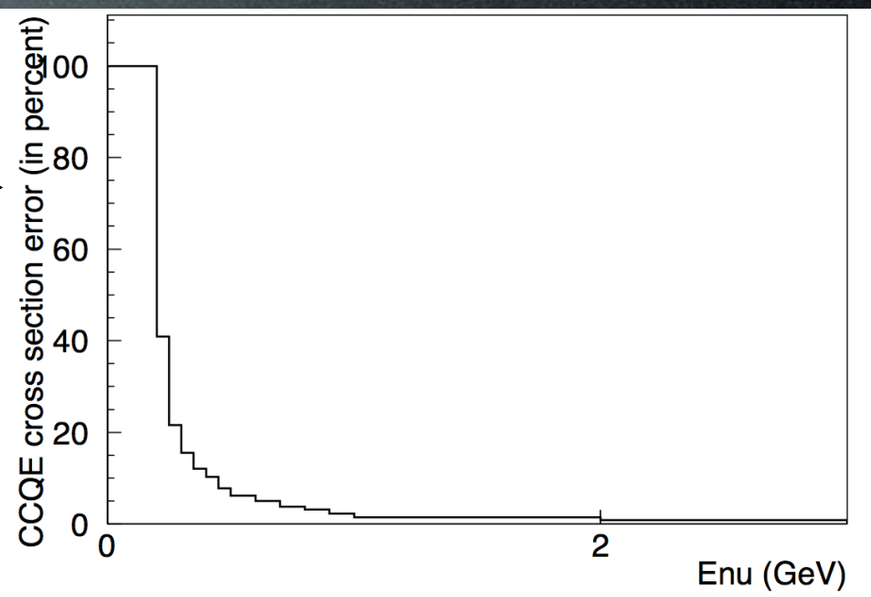


Figure 135: Distance from the T2K fiTQun π^0 rejection cut line for the APFIT selections as described in the text and $2000 < p_e < 5000$ MeV/c.

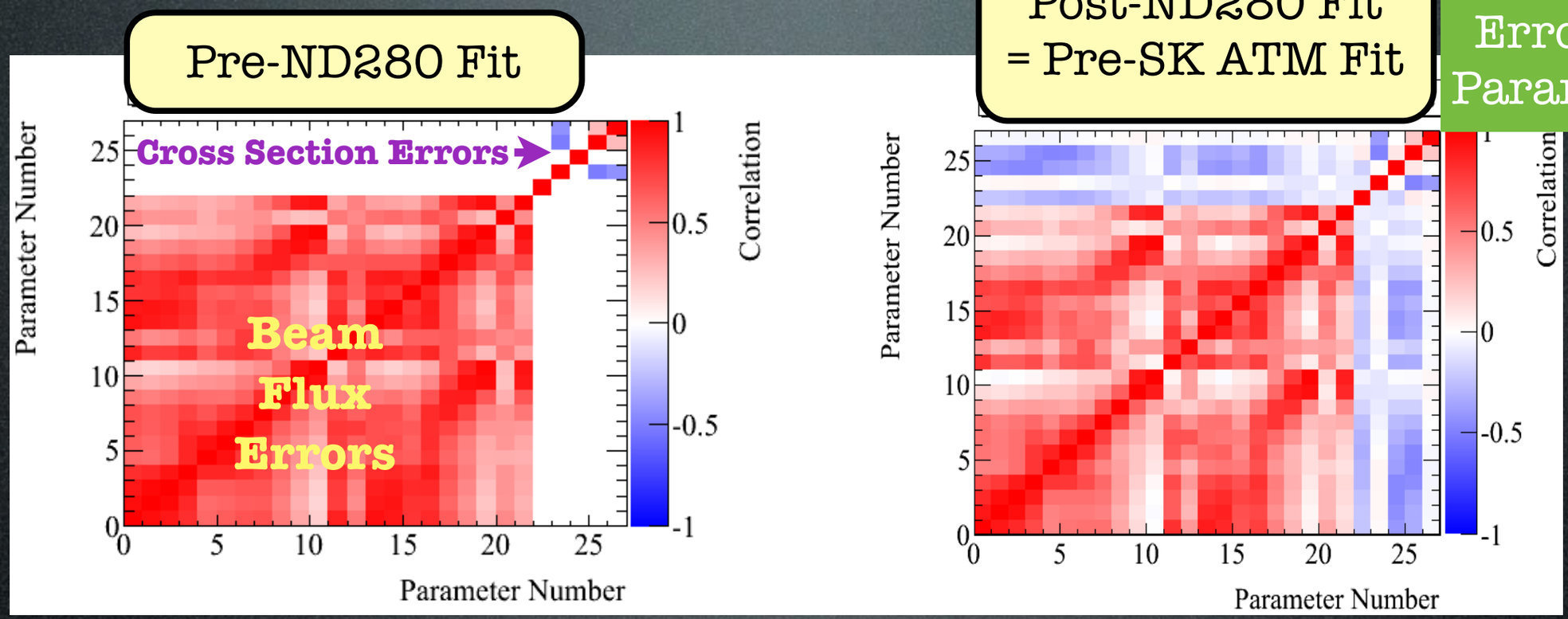
Cross Section Errors

Systematic parameter (α^k)	Error type	σ_{α^k} Uncertainty
α^{CCQE}	CCQE cross section error	
$\alpha^{\mathrm{NormLowE}}$	Flux normalization error in $E_{true} < 1$ GeV	25%
$\alpha^{\mathrm{NormHighE}}$	Flux normalization error in $E_{true} \geq 1$ GeV	15%
α^{CCnQE}	CC non-QE cross section error	20%
$\alpha^{\sigma(\nu_\mu)/\sigma(\nu_e)}$	$\sigma(\nu_\mu)/\sigma(\nu_e)$ cross section error	5%
α^{NC}	NC cross section error	20%



- Current neutrino cross section parametrization does not match what is used in ND280
- These errors are included in the atmospheric fit and then marginalized
  - In some sense, we are double counting cross section errors
- If we continue to use the SK atm data to set systematic errors, this needs to be updated

Joint SK Detector + Cross Section Error Matrix



- We can use ND280 fit as input into SK atmospheric fit, and produce a joint SK detector & cross section error matrix
  - Requires using ND280 cross section parametrization in SK atmospheric fit
  - Energy distribution of SK atmospheric events is different than T2K energy distribution
    - Can cross section model parameters from ND280 fit span this difference?
    - Other cross section errors are likely required
- SK atmospheric flux parametrization may also need to be updated
- Significant work! But may be possible for short term analyses

Longer-Term Plan

- Fundamentally, detector errors are due to **detector mismodeling**
- We currently make several simplifications in detector modeling, e.g.
  - No time-dependent MC (data is corrected at the reconstruction level)
  - No PMT-by-PMT gain calibration (data corrected in reconstruction)
  - Reflections, water quality, PMT acceptance, etc. are mostly uniform across the tank (exception: absorption is linear with depth)
  - ...
- To reduce (and make more correct!) our current errors, we will likely need to refine the details of the **calibration and simulation**

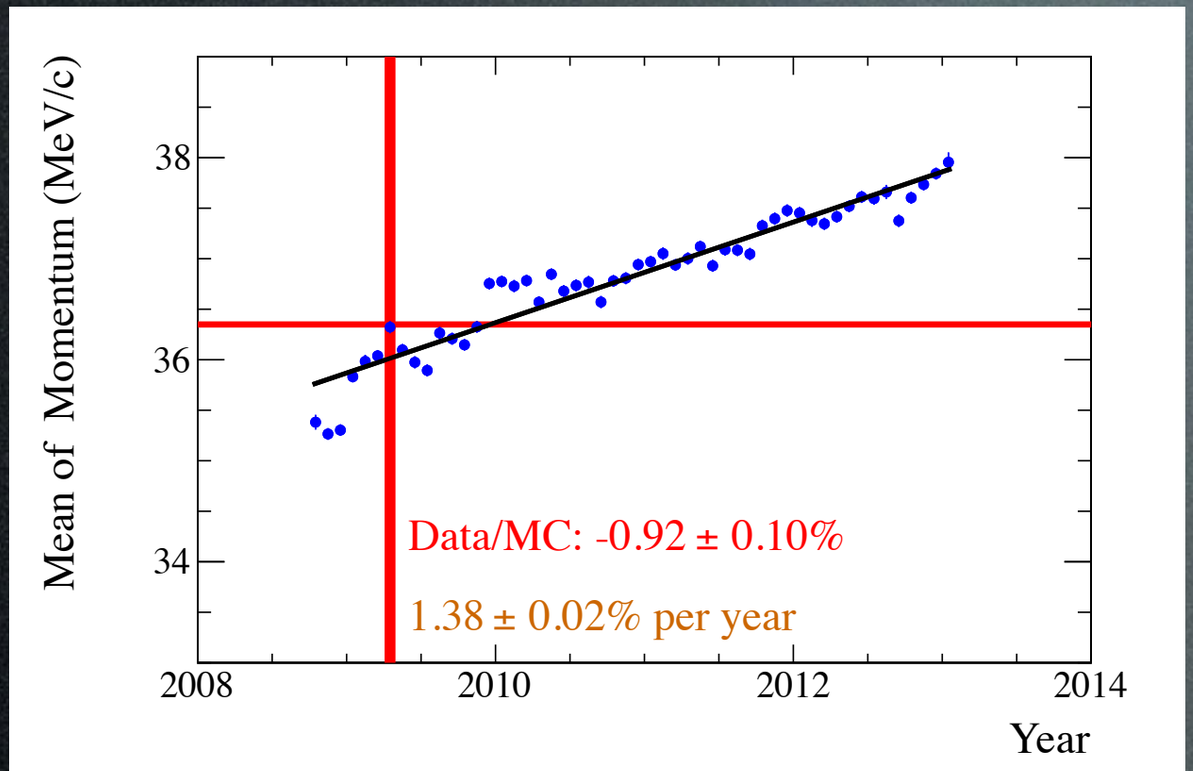
Longer-Term Plan II

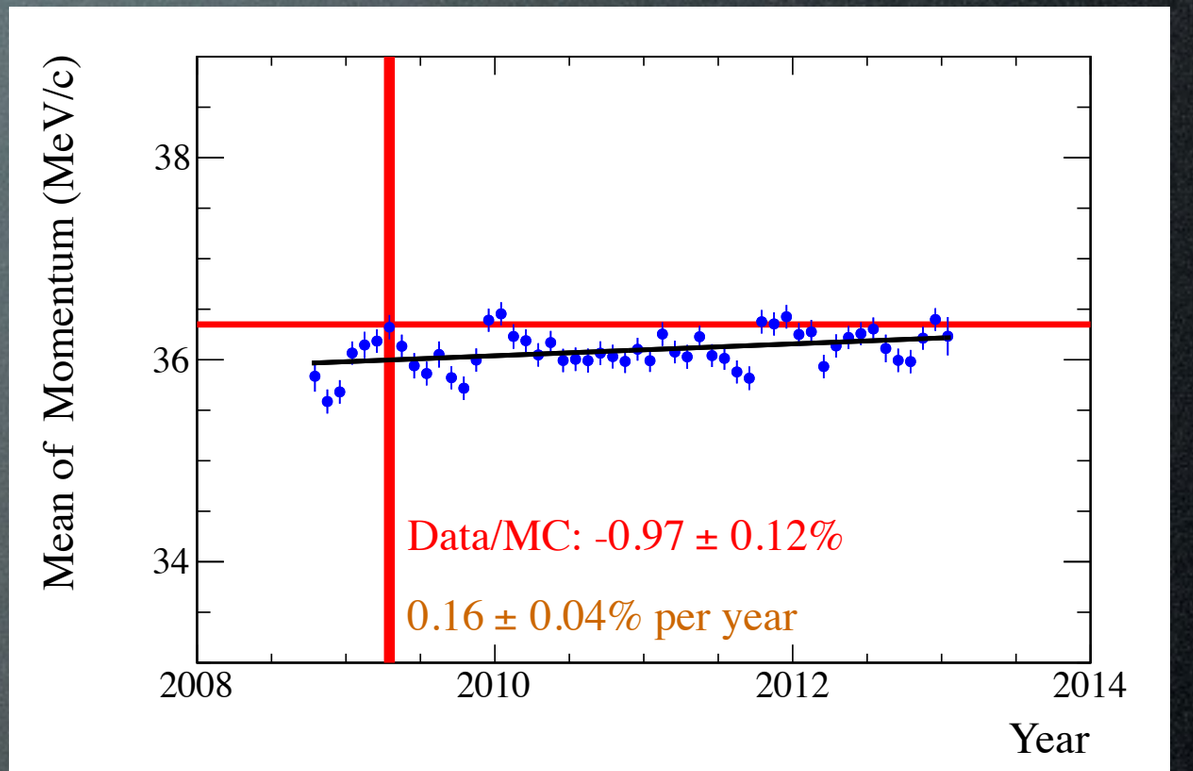
- In principle, it should be possible to account for all detector uncertainties by **propagating uncertainties in the detector modeling**
  - Water quality (top-bottom asymmetry), PMT performance (angular acceptance, QE, charge response), reflectivity of PMTs an black sheet
  - i.e. perform variations of low-level parameters, and constrain these parameters with side-band and calibration samples
    - This requires a sufficient understanding of how to **parametrize the detector performance**
      - Stopping cosmic and hybrid samples will play an integral role here
- This requires a significant undertaking, but there is already a lot of good work to draw from within the Super-K calibration group
  - Perhaps, if we get the ball rolling on this, we can attract the help of others within SK
- If this can be accomplished, this method will provide SK detector errors for all analyses

More Hybrid Samples?

- Hybrid pi0 sample address the efficiency for finding a low energy ring the presence of a high energy ring
    - The low energy electron must be selected in the first place to create the sample, so absolute photon detection efficiency is not tested
- Will a hybrid CC+ sample be sufficient to determine data/MC differences in selection efficiency?
    - Since the cases we are most worried about probably have either a low energy muon or a low energy pion, this is probably sufficient
- Can hybrid samples be extended to multi-ring events?
    - i.e. choose a “2-ring” event and add an additional ring to test the 3-ring efficiency?
- Should we revisit data-data hybrid samples?
    - A large number of low energy single-ring electrons are available from cosmic muon Michels and solar event triggers
- What else do we need to do to understand detector uncertainties for multi-ring events?

Detector Calibration





- Since our e appearance analysis, FiTQun corrects for PMT gain changes over time
  - APFit-like water quality correction is also now available
- Are these two time-based corrections of the data at the reconstruction level sufficient for our short-term analyses?
- Do we need to use detector calibration data to develop more precise corrections?
  - How important is generating time-dependent MC in the short term?
    - For T2K analyses, this may be less important due to SK4 stability

Manpower Assessment

- Short term
  - FV determination and errors: **A. Missert & Z. Liptak**
    - Additional help may be needed to extend this to multi-ring samples
  - Cosmic muon studies: **S. Tobayama & Y. Suda**
  - Hybrid-pi0: **Z. Liptak**
  - Hybrid-CCπ^+: **S. Berkman**
  - Hybrid-multi-ring events: **??**
  - Update SK atmospheric fit to include updated cross section and flux modeling: **X. Li**
- Longer term
  - Testing effects of detector parameters on high level variables: **C. Vilela**
  - Determining relevant uncertain detector parameters from calibration data: **G. Santucci (R. Tacik?)**
  - Development of SK calibration database to store time-dependent detector calibrations: **SBU**
- What other topics need urgent attention?

Summary

- To address the needs of current fiTQun analyses, short and long term plans for improving the SK detector errors are needed
  - Short term: updated SK atmospheric fit and more extensive use of hybrid and control samples
  - Longer term: detector-parameter-based errors, initially set by calibration data and constrained by hybrid and control samples
- Additional thought is needed for the detector errors for the atmospheric neutrinos and $p \rightarrow e^+ \pi^0$
  - What is needed to replace the SK atm fit for these detector errors?
  - Are hybrid samples sufficient?
- Getting started on a detector-parameter-based method will hopefully entice new collaborators within T2K and SK