T2K-SK
Status and Outlook

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Overview

- **T2K-SK Event Selection**
  - Current Selection
  - Future Improvements
- **T2K-SK Systematic Errors**
  - Current Errors
  - Future Improvements
- Topics to address:
  - Consider an exposure of $2 * 10^{22}$ POT
    - 50% ν, 50% anti-ν
  - What is required for percent-level Super-K detector systematic errors?

Current Event Selection

- Designed to select CCQE-like events

Expanding the Selection

- CP violation sensitivity is limited by ν_e statistics
  - Current ν_e selection efficiency is **66%** (assuming 2 m fiducial volume cut)
- Cuts with the most efficiency loss:
  - Single-ring (86.7%)
  - Zero Michels (89.1%)
  - E_{rec} < 1250 MeV (95.9%)
  - fiTQun π^0 cut (92.0%)
- Further Improvements
  - Expanding the fiducial volume
    - ~30% of SK ID volume is not used
  - Improved reconstruction (fiTQun)
    - Better PID, ring-counting, etc.

T2K-SK ν_e Selection

	MC total	$\nu_\mu + \overline{\nu}_\mu$ CC	$\nu_e + \overline{\nu}_e$ CC	$\nu + \bar{\nu}$ NC	$\nu_\mu \to \nu_e$ CC
interactions in FV	656.83	325.67	15.97	288.11	27.07
FCFV	372.35	247.75	15.36	83.02	26.22
(1) single ring	198.44	142.44	9.82	23.46	22.72
(2) electron-like	54.17	5.63	9.74	16.35	22.45
(3) $E_{\rm vis} > 100$ MeV	49.36	3.66	9.68	13.99	22.04
(4) no Michel election	40.03	0.69	7.87	11.84	19.63
(5) $E_\nu^{\rm rec} < 1250$ MeV	31.76	0.21	3.73	8.99	18.82
(6) not π^0-like	21.59	0.07	3.24	0.96	17.32

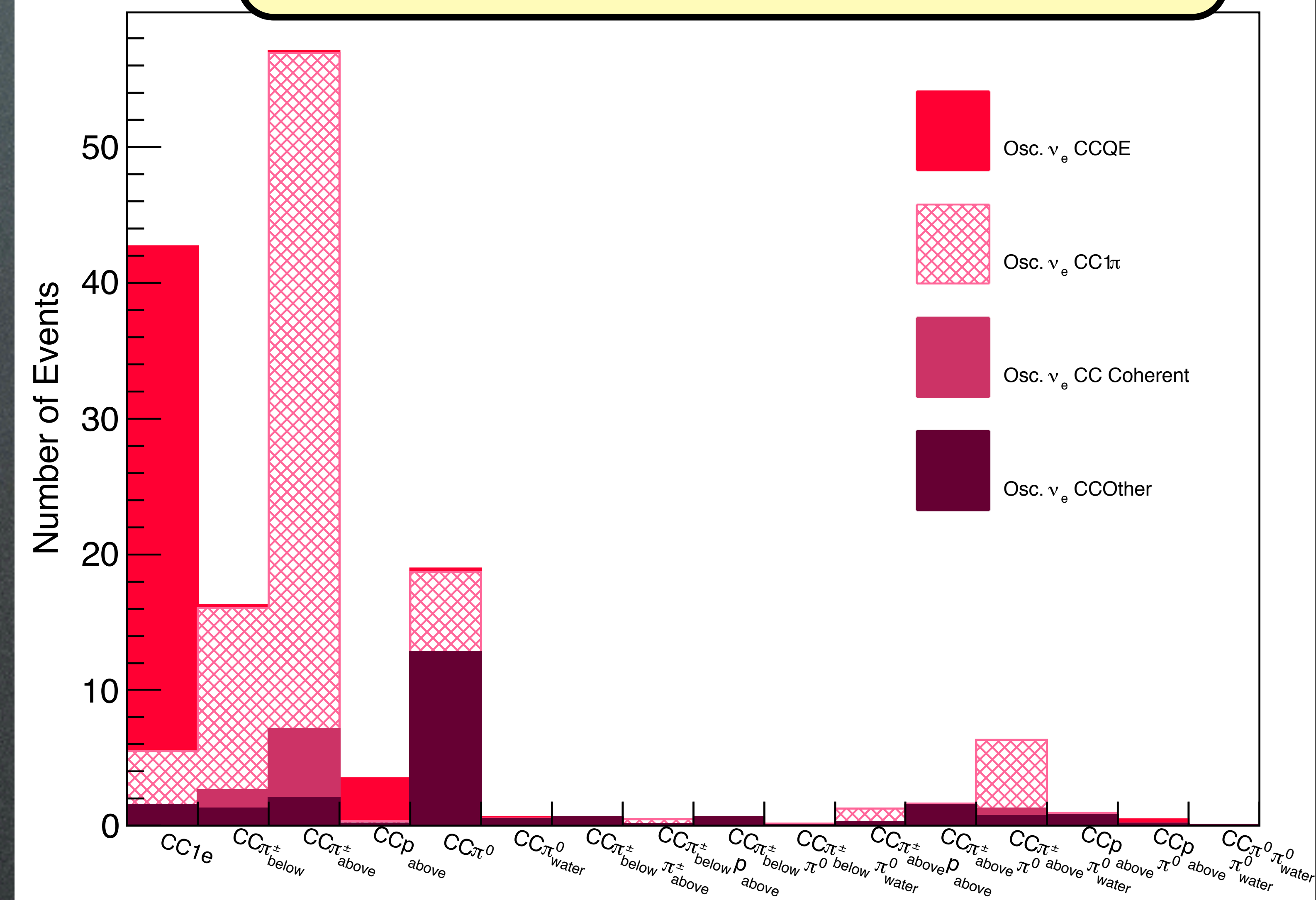
264/399 events expected for 10^{22} POT

(assuming $\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2, $\delta_{CP} = 0$, $\Delta m^2_{32} > 0$)

Which Event Topologies are Being Lost?

- Percentages relative to current signal:
- CC1e (16%)
- CCπ^+ (28%)
- CCπ^0 (7%)
- CCπ^+ with $\pi^+ \rightarrow \pi^0$ (2%)
- Other (2%)

Number of Events Cut at 10^{22} POT



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Zero Michels Cut

- By loosening this cut, can accept ν_e-CCπ^+ events with a π^+ below Cherenkov threshold
  - Can reconstruct neutrino energy assuming a Δ recoil
- Adds 13% more signal with similar purity
- Further improvement may be possible using fiTQun

No Decay Electron (Nominal)

Sig. CC (17.83)	**QE**	**15.84**	$\nu_e+\overline{\nu}_e$ CC	QE	2.43
	1π	**1.91**		1π	0.41
	Coh	**0.05**		Coh	0.01
	Oth.	**0.03**		Oth.	0.04
$\nu_\mu+\overline{\nu}_\mu$ CC	QE	0.05	NC	$1\pi^0$	0.78
	1π	0.02		$1\pi^\pm$	0.15
	Coh	0		Coh	0.21
	Oth.	0.001		Oth.	0.36
TOTAL	22.29				

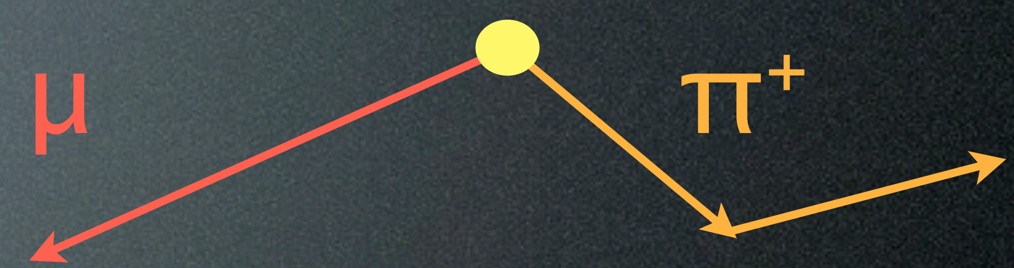
Purity =17.83/22.29 = 80 %

One Decay Electron (New)

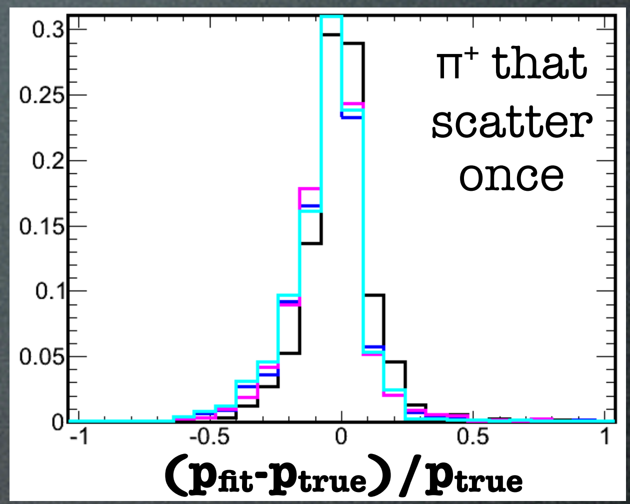
Sig. CC (2.30)	**QE**	**0.02**	$\nu_e+\overline{\nu}_e$ CC	QE	0.003
	1π	**1.94**		1π	0.32
	Coh	**0.25**		Coh	0.04
	Oth.	**0.09**		Oth.	0.03
$\nu_\mu+\overline{\nu}_\mu$ CC	QE	0.17	NC	$1\pi^0$	0.01
	1π	0.07		$1\pi^\pm$	0.05
	Coh	0.001		Coh	0
	Oth.	0.009		Oth.	0.09
TOTAL	3.08				

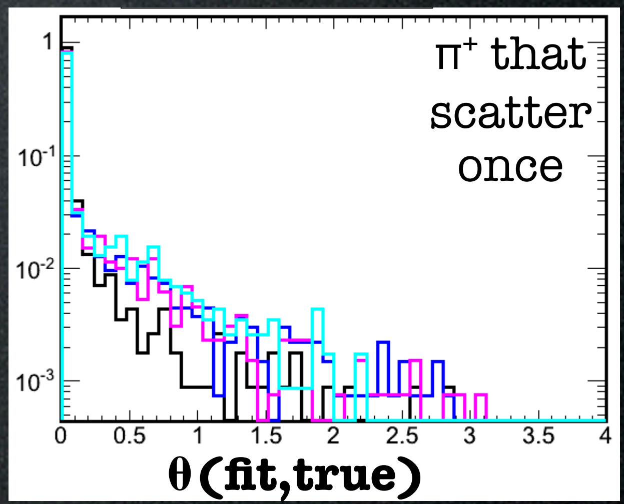
Purity = 2.30/3.08 = 75 %

Single Ring Cut

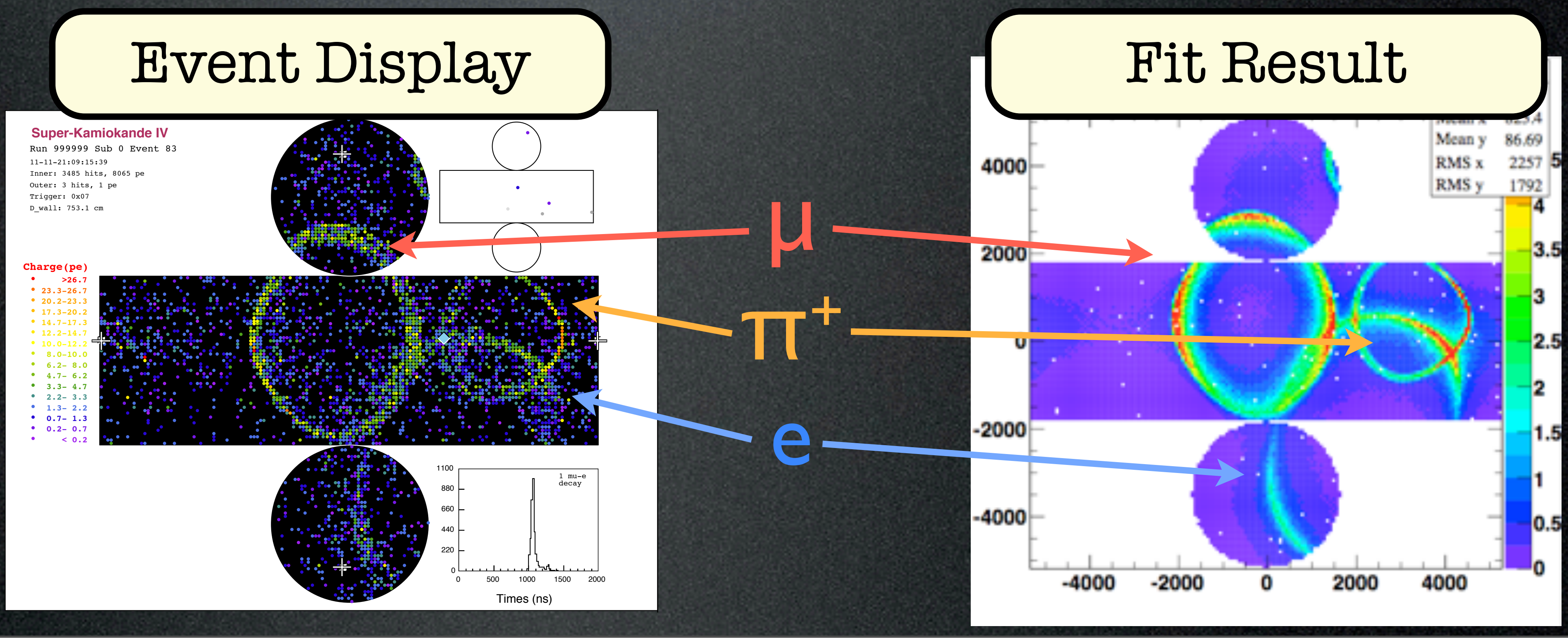


- Remaining CCπ+ events can be recovered using a CCπ+ under development
  - π+ are allowed to scatter
- Multi-ring fitting is also greatly improved
  - 3-ring fits can recover CCπ0 events
  - Already under study for p->e+π0



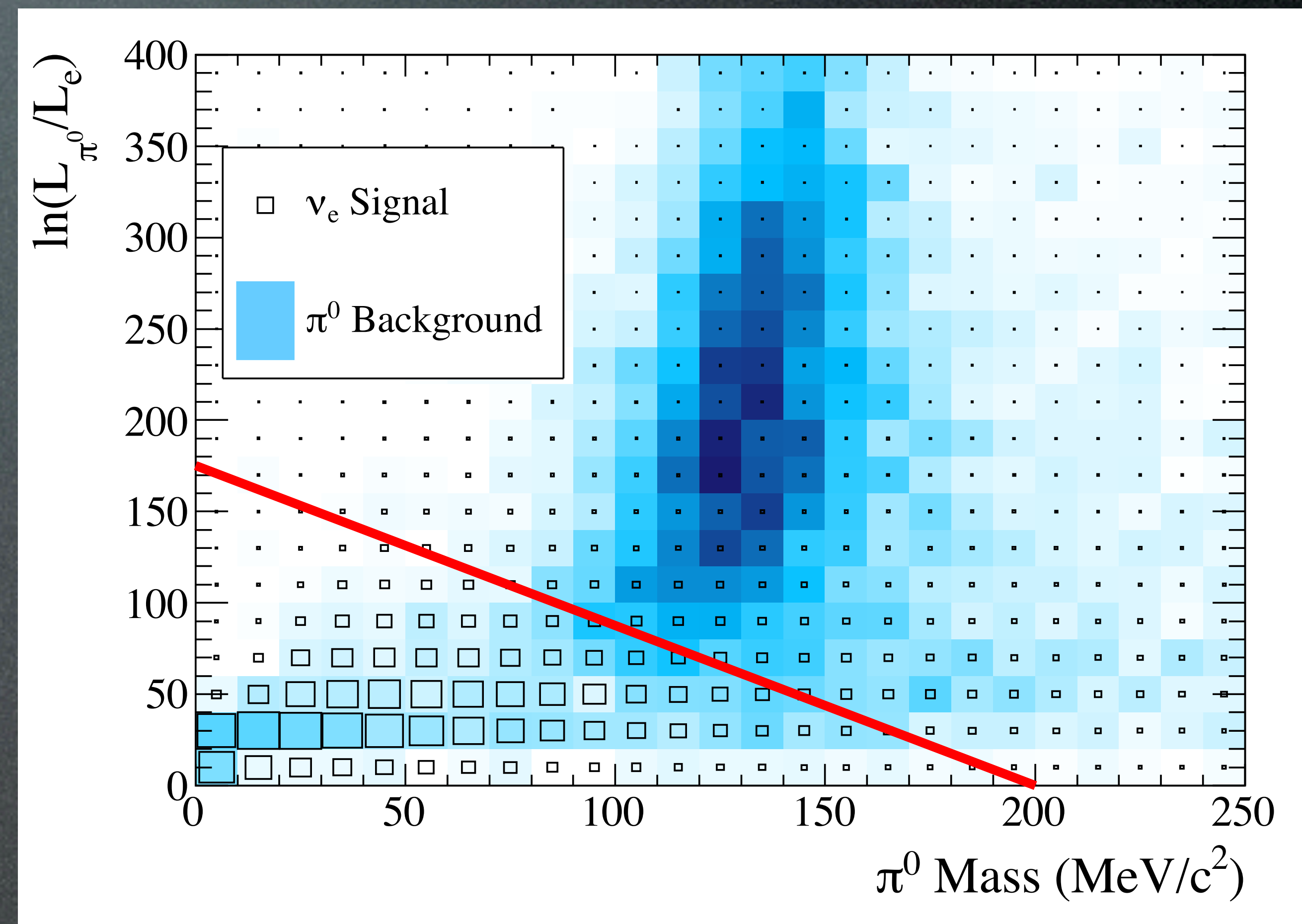


Improved multi-ring fits



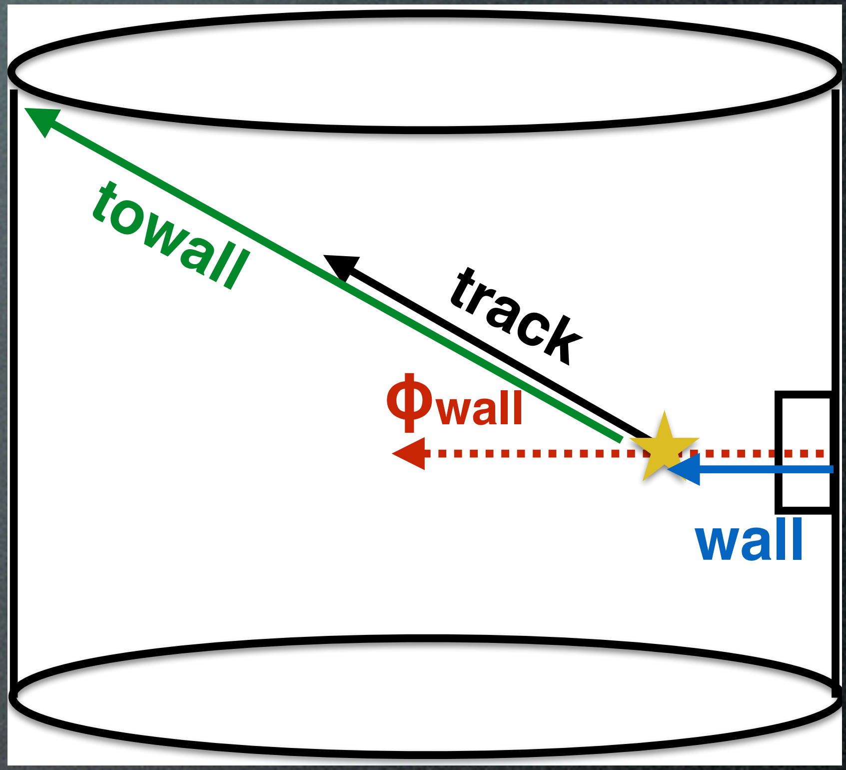
π^0 Cut

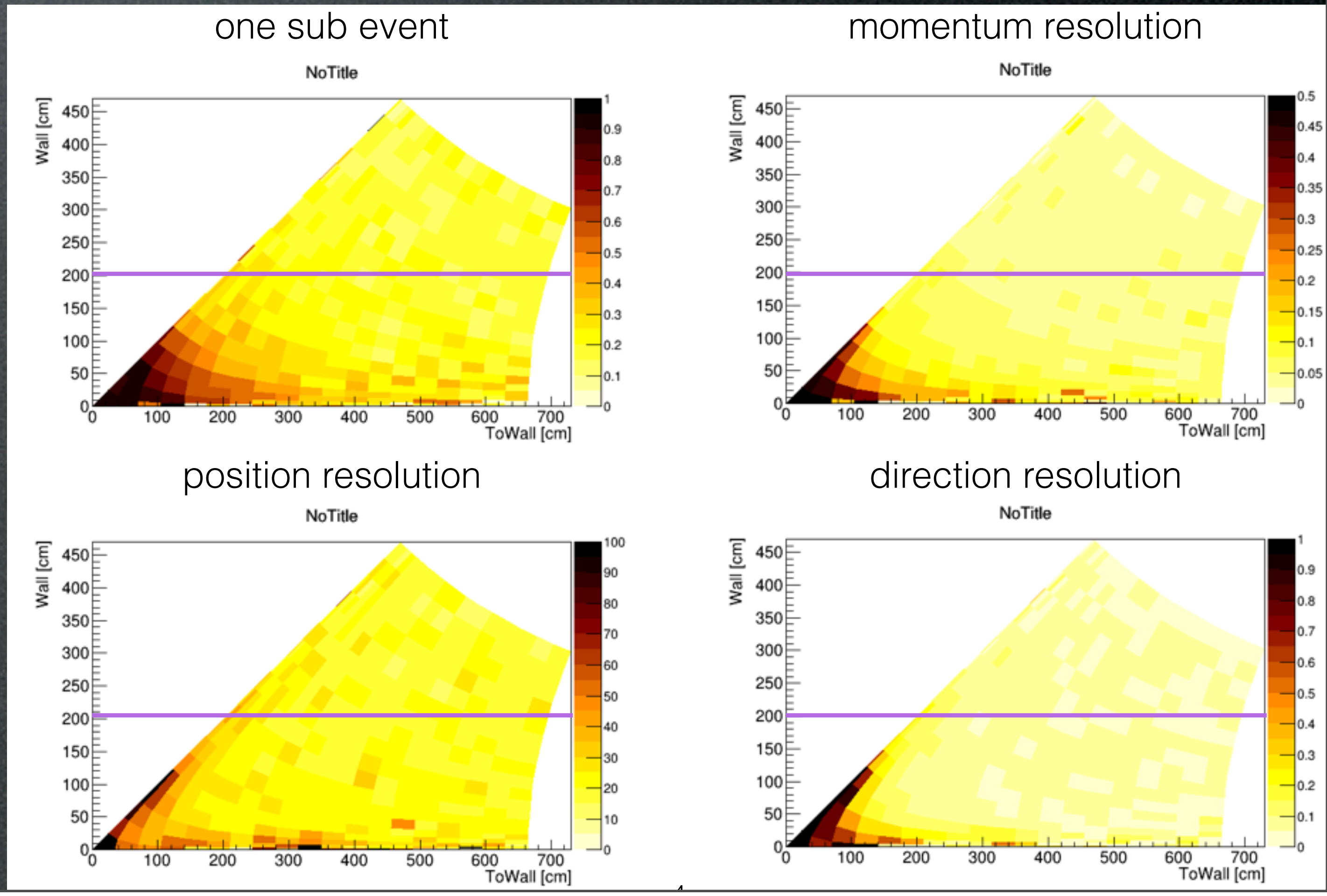
- Initial cut was tuned for ν_e appearance search
  - 8% signal loss was acceptable for stronger π^0 background rejection
- For CP violation search, more π^0 background is acceptable
  - Particularly with 50/50 ν/anti-ν running
- Additional improvements can also increase the efficiency
  - e.g. moving the cut as a function of E_{rec}
- May allow us to remove E_{rec} cut completely (4% of signal)



Expanding the Fiducial Volume

- Current FV cut removes all events with a reconstructed vertex within
  2 m of the tank wall
    - Removes 30% of the total inner detector volume
    - For events pointed away from the wall, this is excessive
    - For events pointed at the wall,
      2 m may not be sufficient
- Considering a 2D cut in "towall" and "wall" (see diagram)
    - Remove events where both these values are small

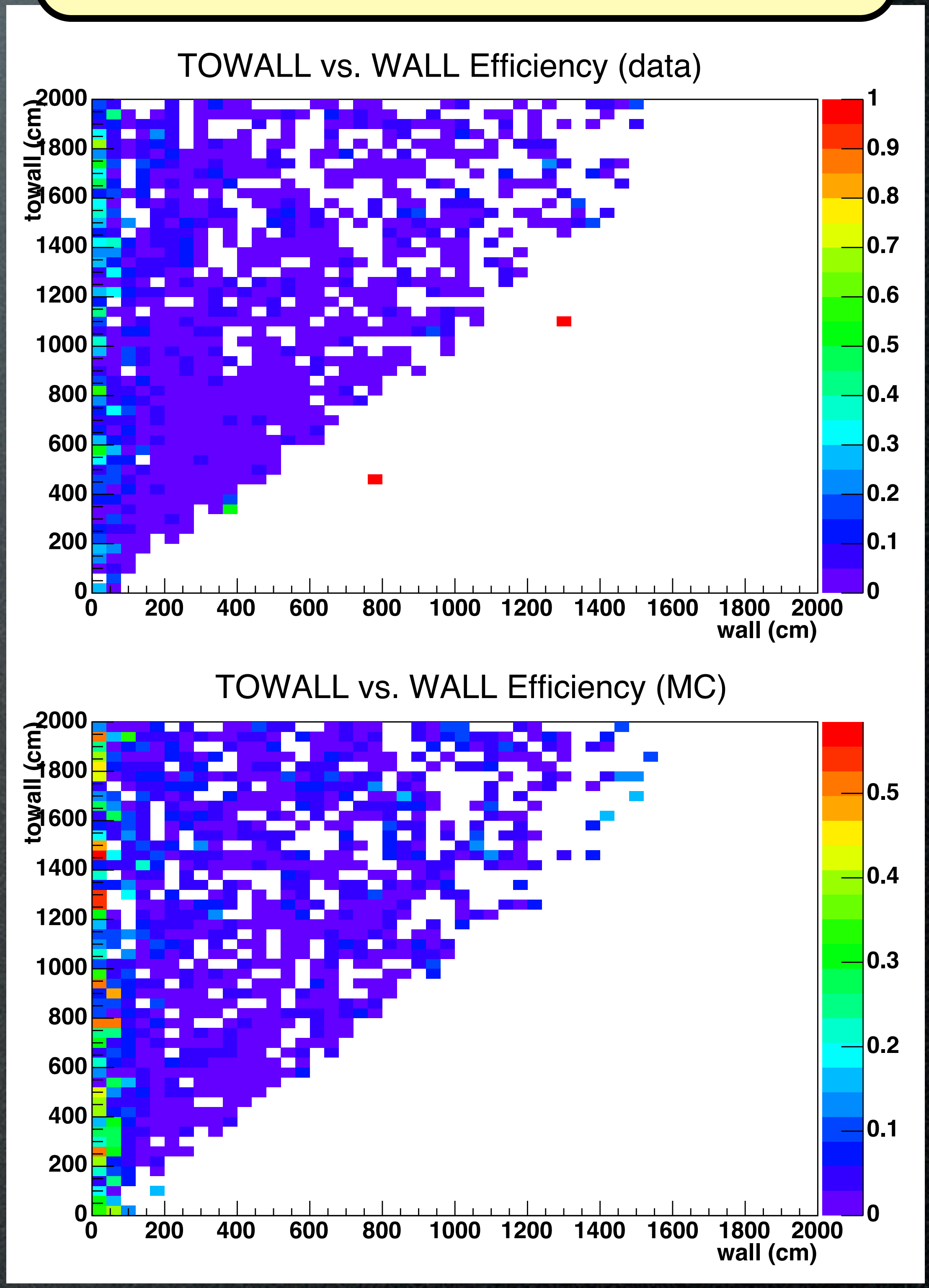




More on Fiducial Volume

- When setting the FV boundary, also need to consider backgrounds
    - π^0's near the wall are more likely to lose a photon
- The hybrid-π^0 sample is being used to constrain this effect
    - Combine a 1-ring e-like event from data with a MC photon
- Entering background falls away at wall near 1 m
    - Could perhaps recover around 15% of events

"Efficiency" to Misreconstruct π^0 events as ν_e



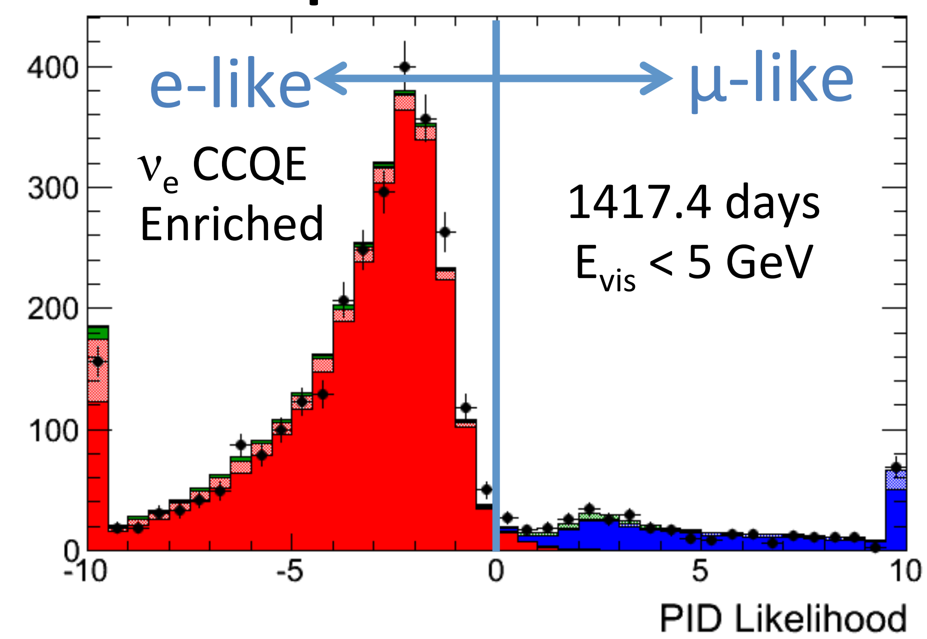
Super-K Detector Systematic Errors

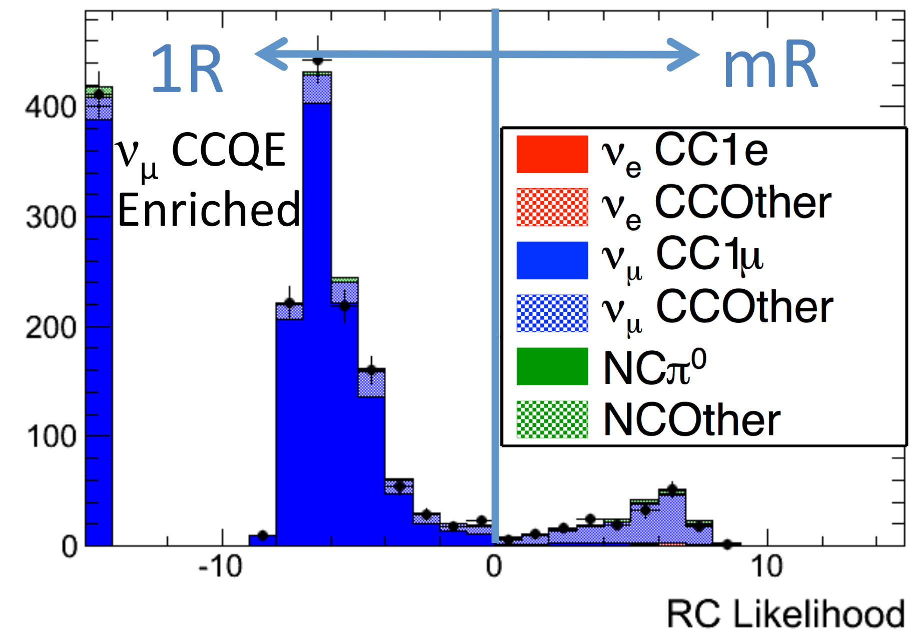
- Current T2K-SK detector errors are largely set by fitting the atmospheric neutrino data
  - Use a T2K-like selection, and determine errors from data/MC differences
  - Current errors on the ν_e sample are 3%
- This method necessarily folds in uncertainties on neutrino interactions and the atmospheric neutrino flux
  - Treatment of these errors directly impacts size of detector systematic errors
- Alternative methods not involving atmospheric neutrinos are under investigation (more later)

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

Atmospheric ν

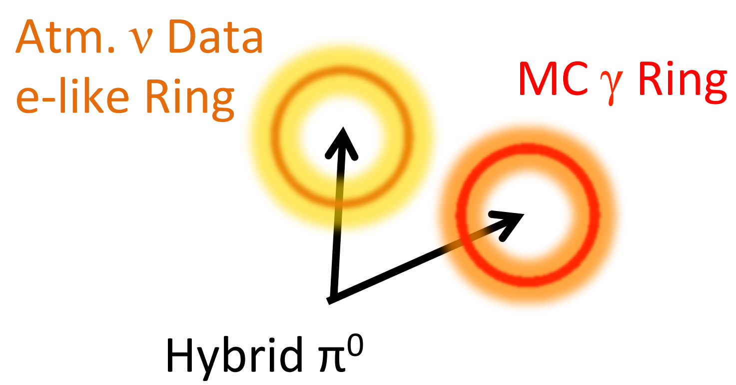




Stopping Cosmic μ

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

Hybrid π^0 Samples

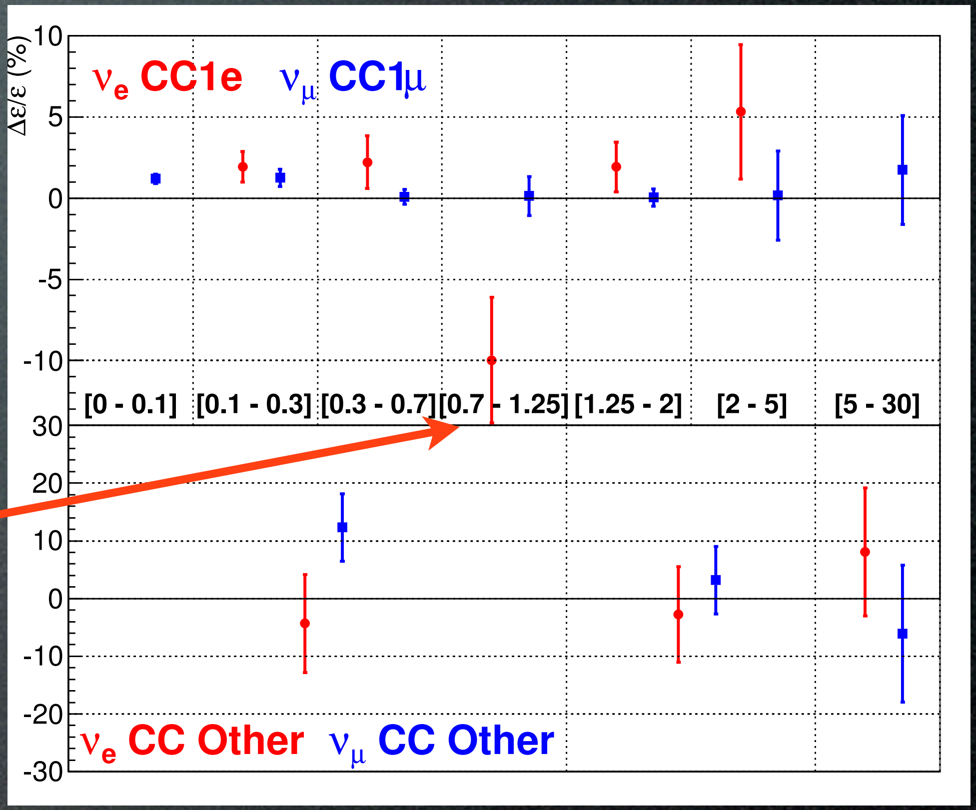


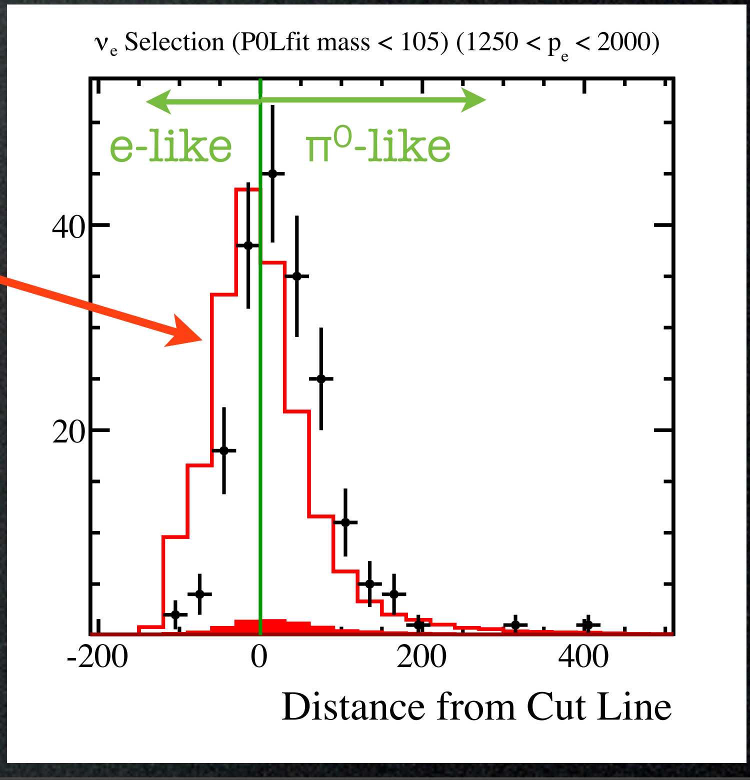
Atmospheric ν

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

Fit Results

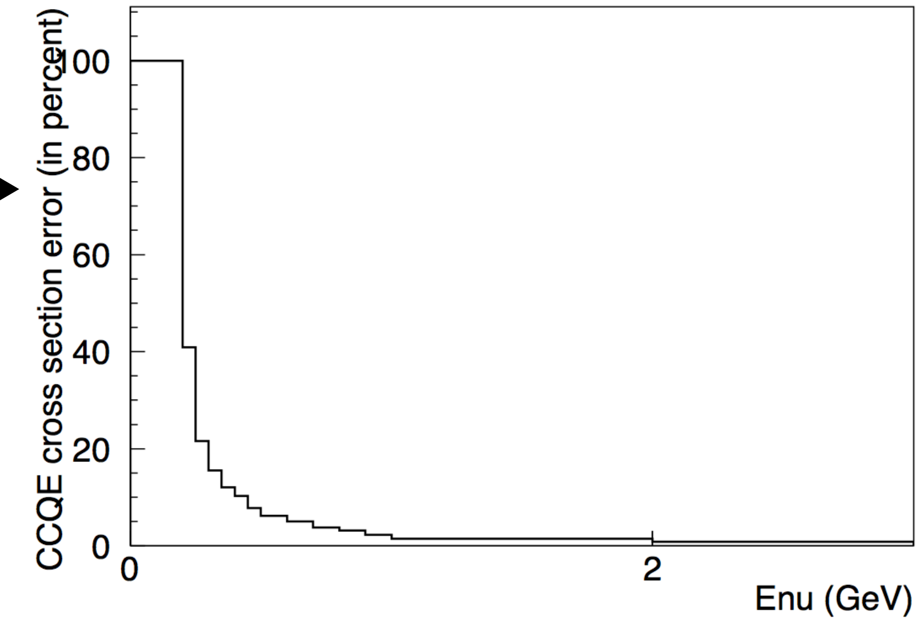
- Uncertainties are calculated in bins of visible energy
- Total detector error is a quadrature sum of:
  - "fit error": the error bar from the fit
  - "shift error": the deviation of the fit value from zero
- Large ν_e shift error seen in the 0.7-1.25 GeV bin
  - Above this energy, the π^0 cut is not 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...





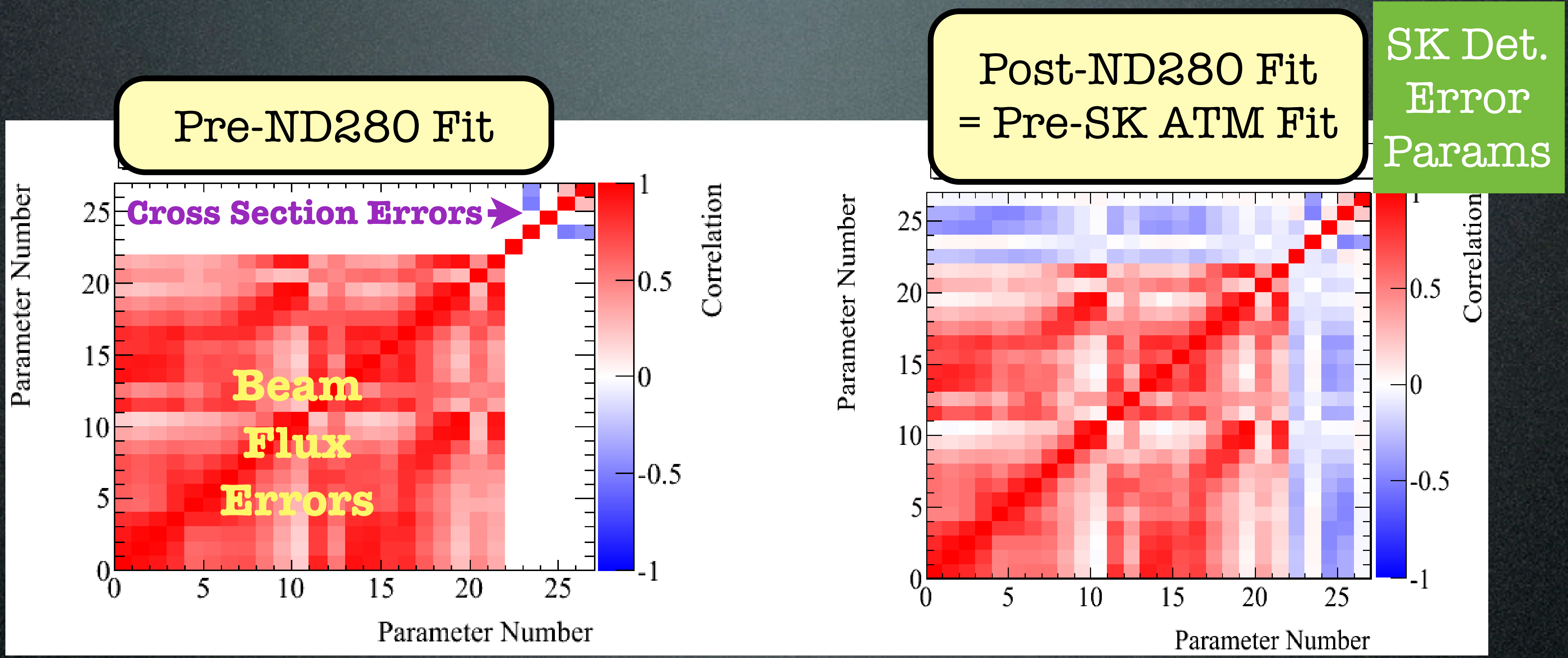
Cross Section Errors

Systematic parameter (α^k)	Error type	σ_{α^k} Uncertainty
α^{CCQE}	CCQE cross section error	
α^{NormLowE}	Flux normalization error in $E_{true} < 1$ GeV	25%
$\alpha^{\text{NormHighE}}$	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
- Ideally, this treatment should be updated to reflect our current understanding of neutrino cross sections

Joint SK Detector + Cross Section Error Matrix



- One possible solution is to 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
- Still need to marginalize over SK atmospheric flux uncertainties
  - SK atmospheric flux parametrization may also need to be updated

Reducing Systematic Errors

- What will happen if we improve the treatment of the atmospheric flux and neutrino cross sections in the atmospheric fit?
  - Will have a **more rigorous treatment** of SK detector errors
  - However, there is **no guarantee this will reduce the errors**
- 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 reach **percent-level errors**, may need to refine the details of the **calibration and simulation**
  - This requires a significant undertaking, but there is already a lot of good work to draw from within the Super-K calibration group

Future Systematic Error Possibilities

- All “detector” errors are due to imperfect modeling of the detector
  - A perfectly understood detector would have no detector systematic uncertainties
- Current method **mixes flux and cross section uncertainties** into the detector uncertainties
- 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**
  - This is the method used in ND280 and even other Cherenkov detectors, such as MiniBooNE
- Likely a **long term project**, but solves many problems if it can be accomplished

Summary

- T2K-SK ν_e statistics increase of 40% to 60% may be possible (my rough guess)
  - $CC\pi^+$ with below Cherenkov pions (~13%)
  - Multi-ring events ($CC\pi^+$, $CC\pi^0$, etc.) (up to 20%)
  - Looser and better π^0 and E_{rec} cuts (~5%)
  - Enlarge the fiducial volume (10-15%)
- Purity may also suffer somewhat
- T2K-SK detector systematic errors are at the 3-4% level
  - Treatment of atmospheric flux and cross section parameters will be improved
  - Possibility to move to a detector-driven approach is under investigations
- To significantly improve the error, more detailed treatment of calibration and simulation may be required