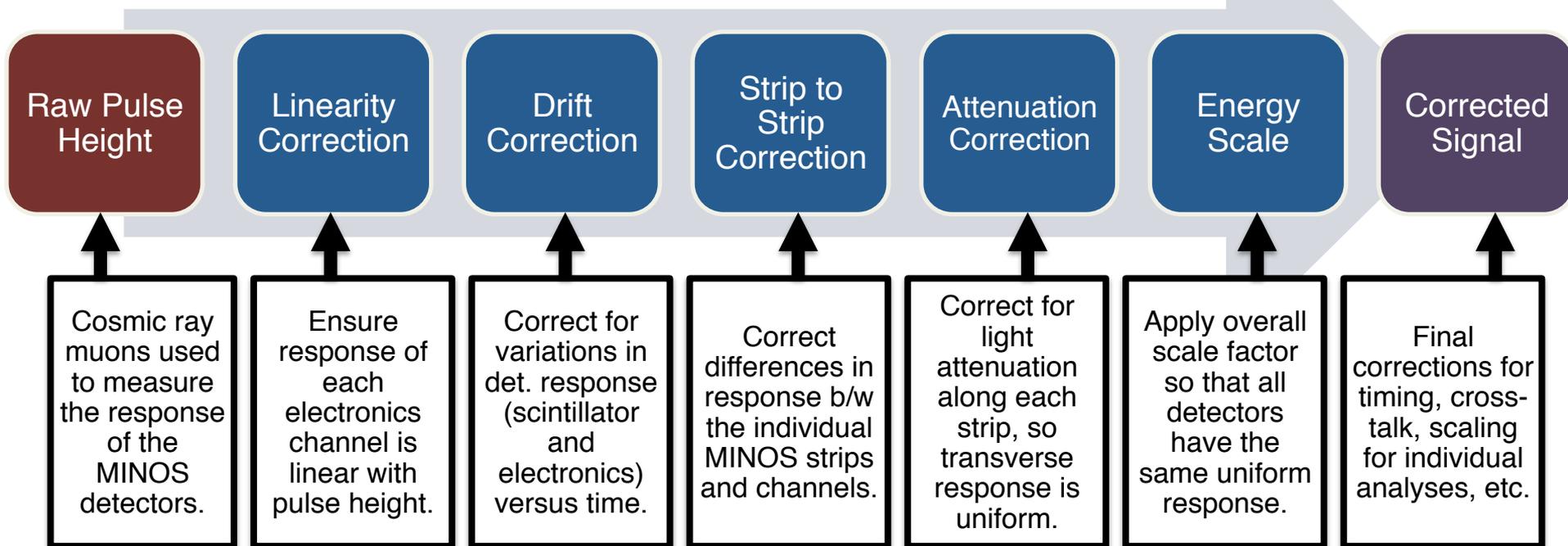




# MINOS+ Calibration Procedure

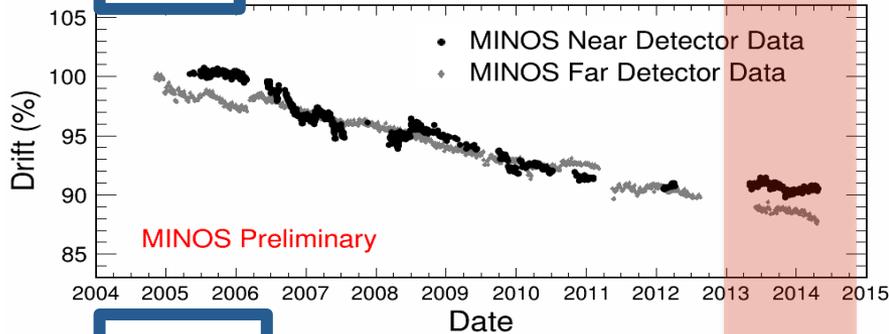
- ❖ The MINOS+ calibration procedure is meant to ensure that for a given energy deposition, the calorimetric response is uniform as a function of time and space, and uniform between the two detectors.
  - The MINOS+ running period began in September 2013.
  - The steps in this calibration are as follows:



# Detector Light Level

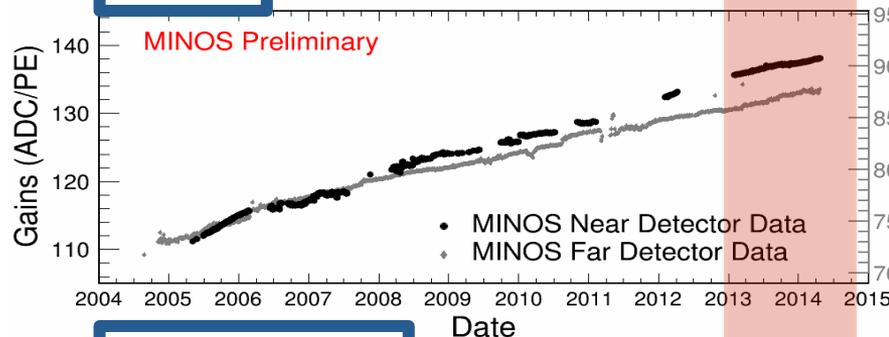


## Drift



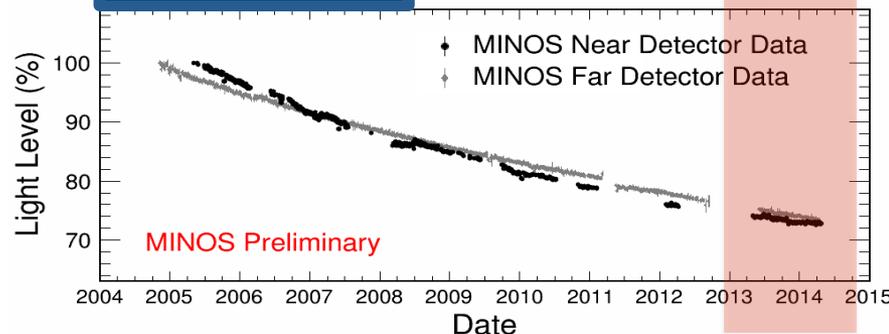
**Drift:** The drift measures the overall response of the detector versus time, including changes in the PMT, electronics, and scintillator. This has decreased by ~10% since 2005.

## Gains



**Gains:** The gains have increased by approx. 3.0 ADCs/PE/year in the Near Detector, and 1.4 ADCs/PE/year in the Far Detector. The increase in gains is theorized to be due to the burning off of dynode impurities by continued PMT current.

## Light Level



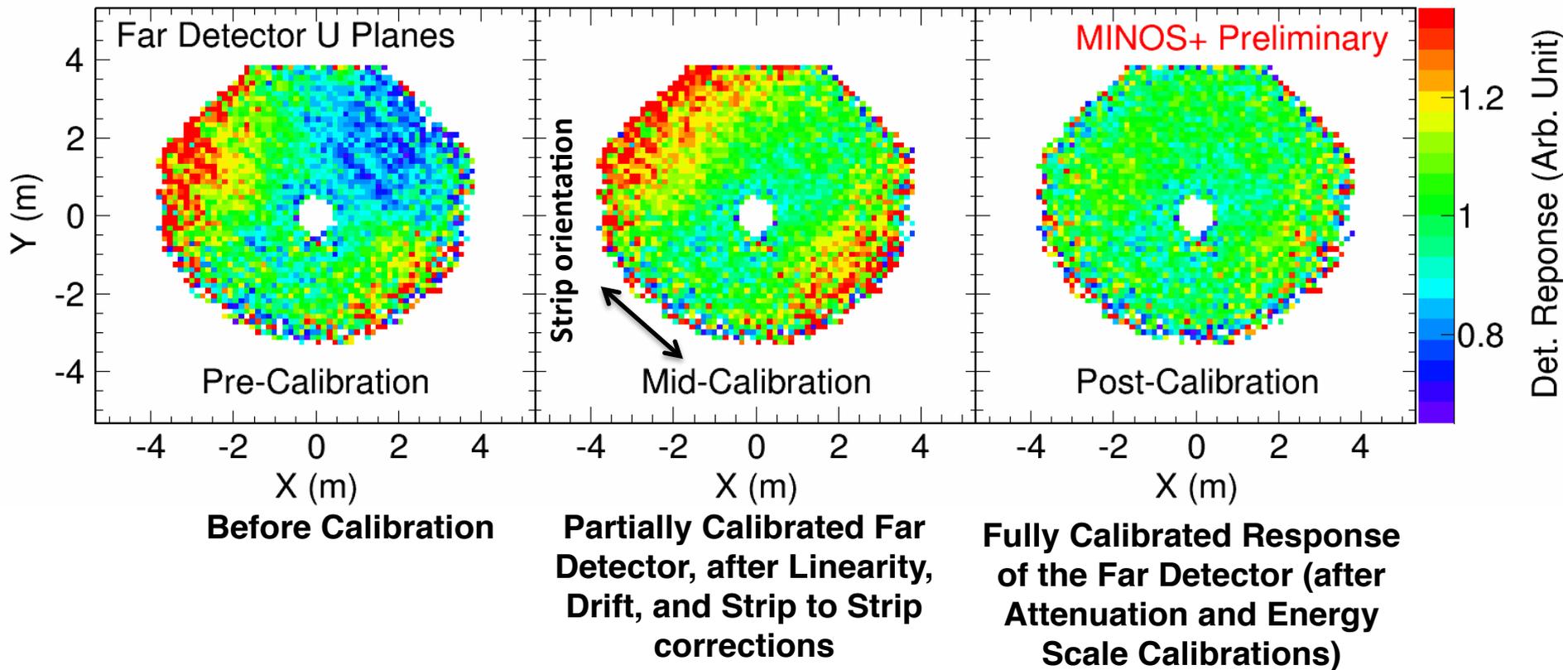
**Light Level:** The detector light level is defined as Drift/Gain. The level has decreased over time, at a rate of 3.0% (3.5%) in the Near (Far) Detector per year, primarily due to the aging of scintillator.

**MINOS+ Era**

# Calibration of the MINOS+ Far Detector



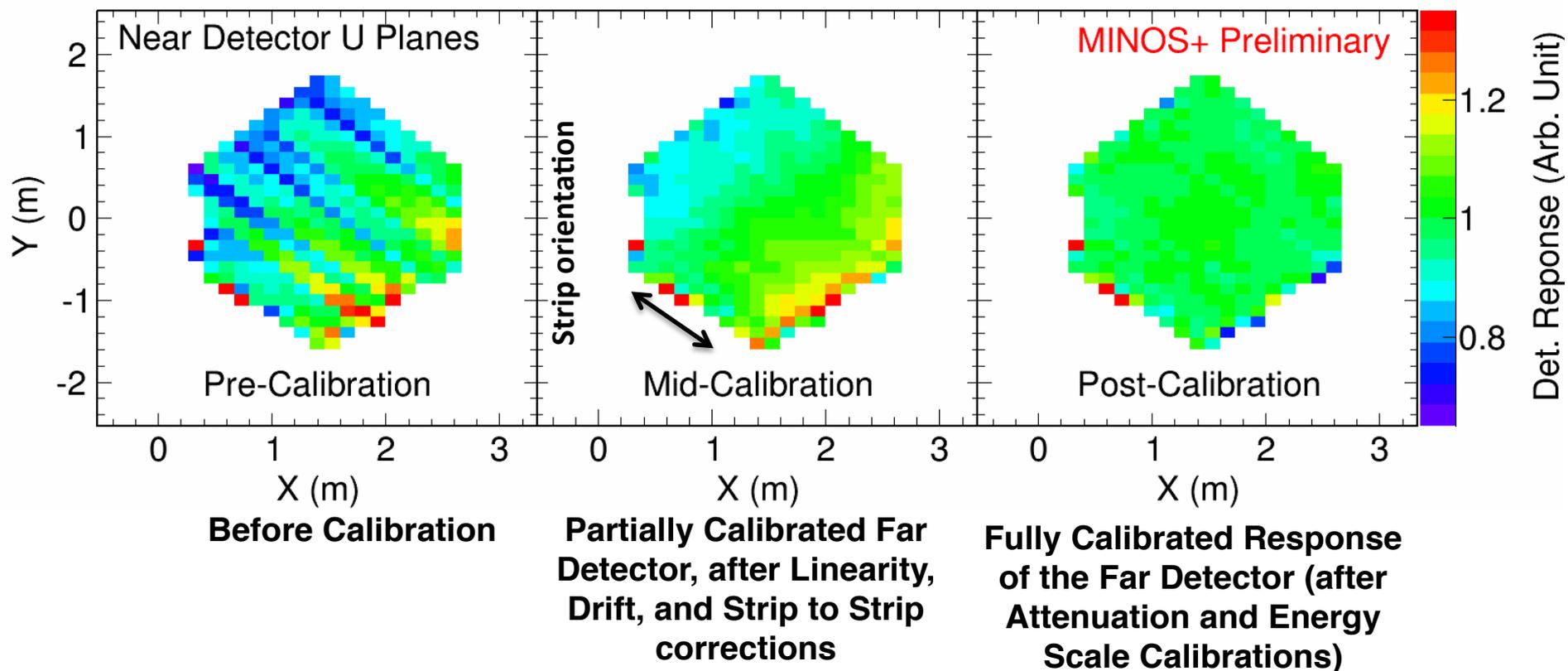
The scintillating strips at the MINOS Far Detector are oriented at  $45^\circ$  to the vertical, and at  $90^\circ$  with respect to neighboring planes. Shown below is the calibration of one of these two views. (The NuMI neutrino beam is travelling out of the page.)



# Calibration of the MINOS+ Near Detector



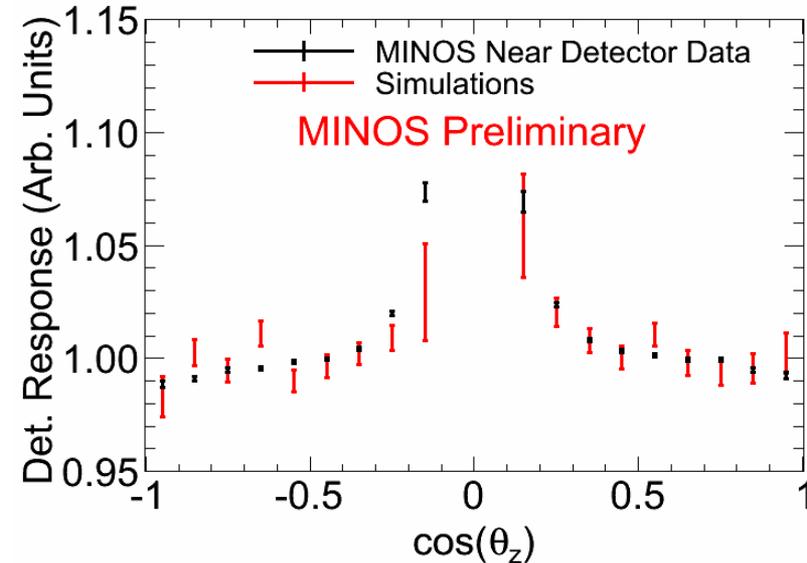
The scintillating strips at the MINOS Near Detector are oriented at  $45^\circ$  to the vertical, and at  $90^\circ$  with respect to neighboring planes. Shown below is the calibration of one of these two views. (The NuMI neutrino beam is travelling out of the page.)



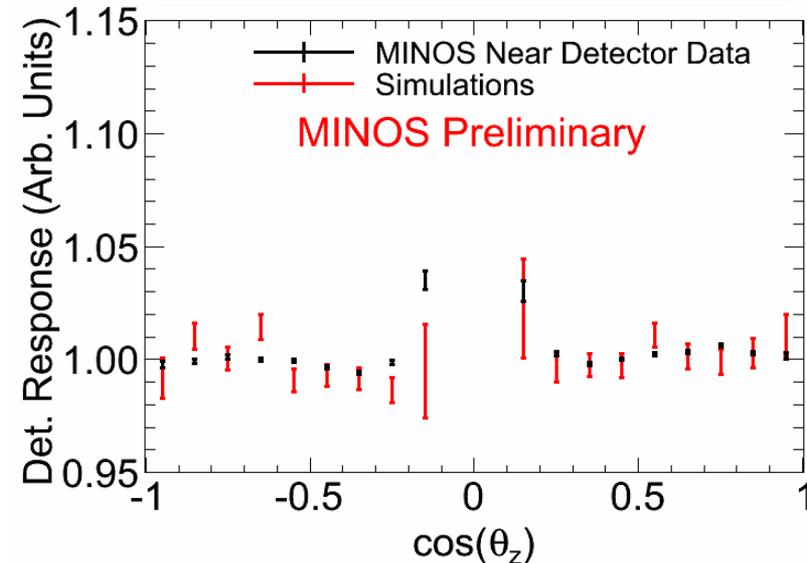


# MINOS+ Angular Corrections

Near Det. Pre-Correction



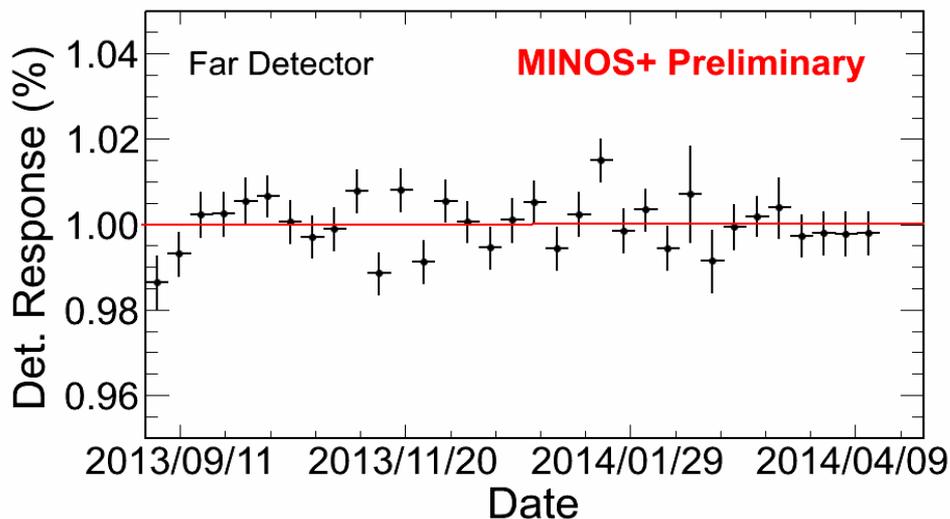
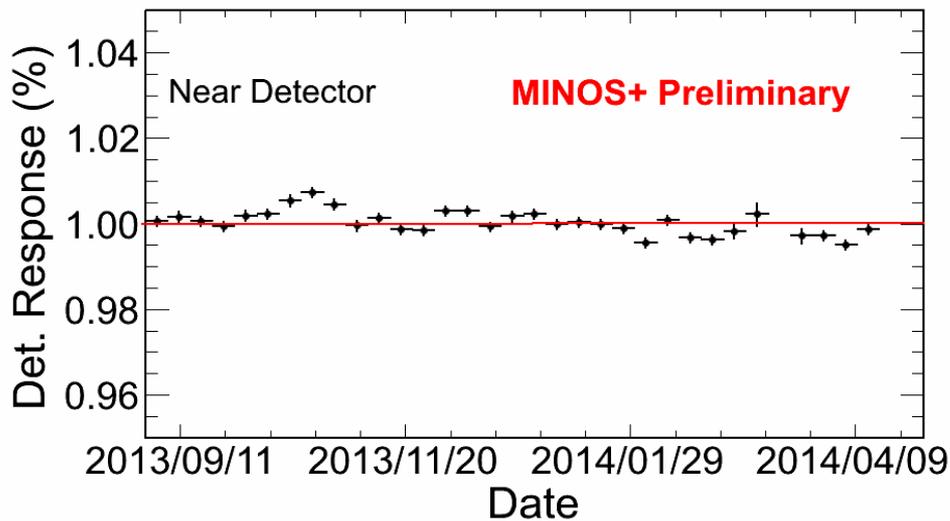
Near Det. Post-Correction



- **Absolute scale factor:** This value is calculated from stopping muons, using  $dE/dx$  for the energy deposition in a window near end of the track.
  - Studies have found that this scaling factor depends on the zenith angle of the incoming cosmic muon.
- For MINOS+, this dependence is removed using an angular correction.
- Following this correction, the scale factors calculated from cosmic and beam muons are closer to one another.

$$\text{fit} = dE_0 \times \left( 1 + b \left[ \frac{1}{\cos \theta} \right] \right)$$

# MINOS+ Calibration Stability



- The calibration as a function of time, as measured using cosmic stopping muons, is stable to within 1% in both detectors.
- The overall systematic error is on the order of  $\sim 1\%$ .

| Systematics       | Near Detector | Far Detector |
|-------------------|---------------|--------------|
| Data vs. MC Shape | 0.25%         | 0.10%        |
| MC Tuning         | 0.42%         | 0.08%        |
| Cosmic vs. Spill  | 0.06%         | -----        |
| Spatial           | 0.30%         | 0.84%        |
| Total             | 1.03%         | 1.02%        |