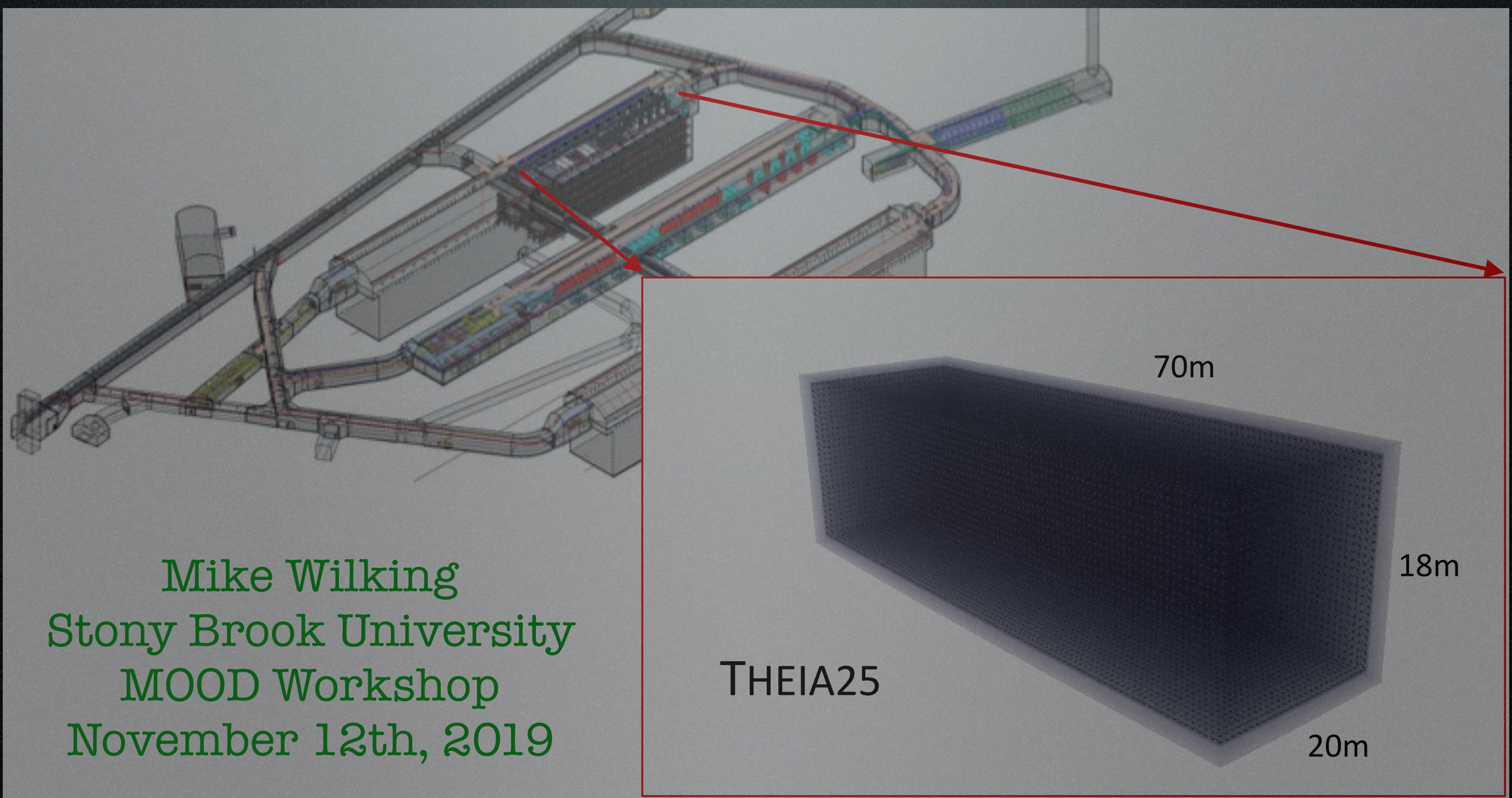
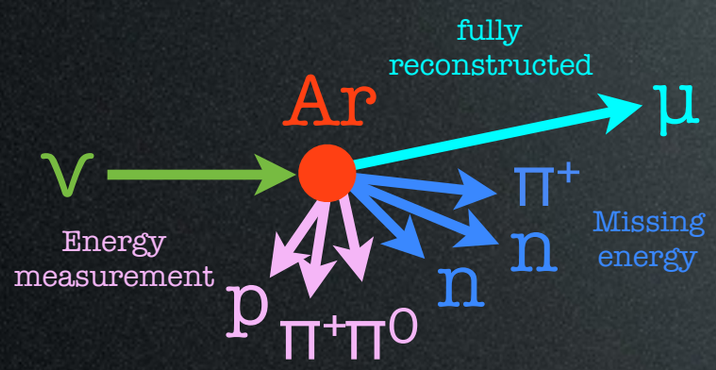
Long Baseline Neutrino Physics with Theia

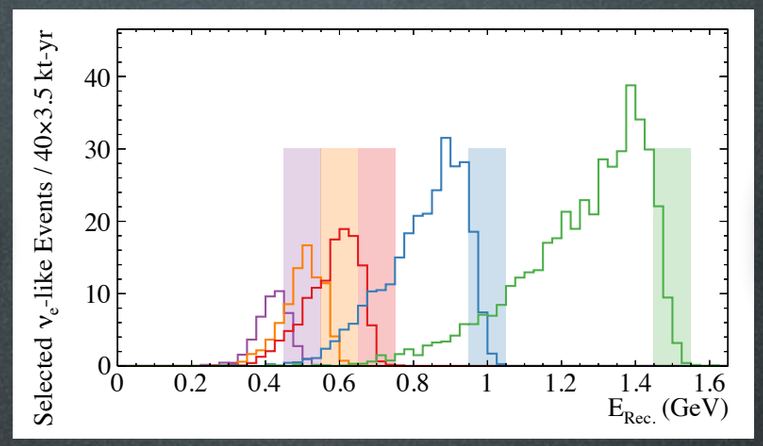


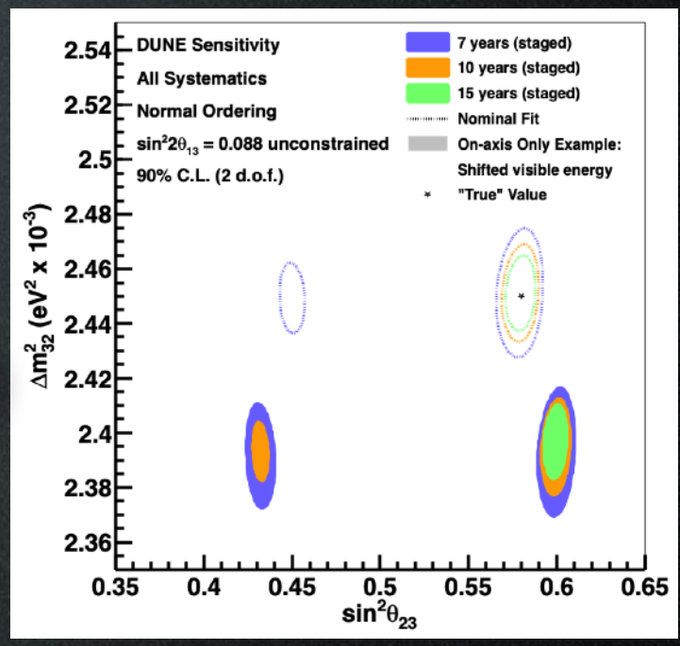
Mike Wilking
Stony Brook University
MOOD Workshop
November 12th, 2019

Challenges in DUNE LBL Physics



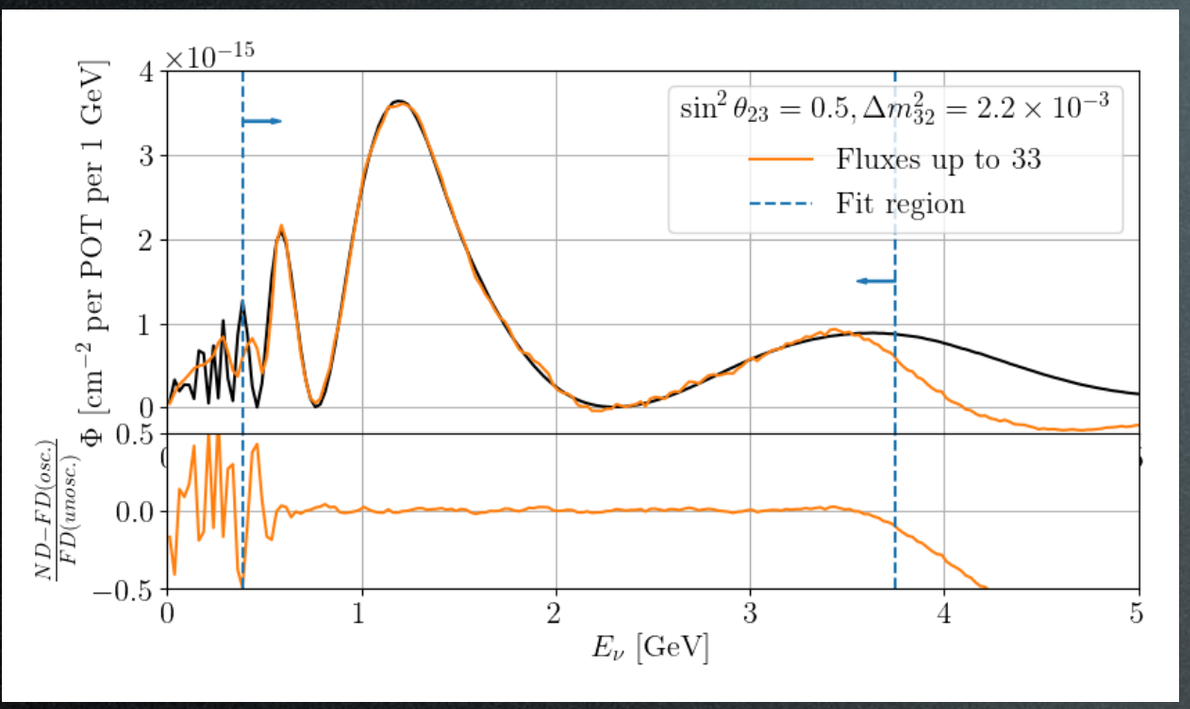
E_{rec} for selected E_{true} bins

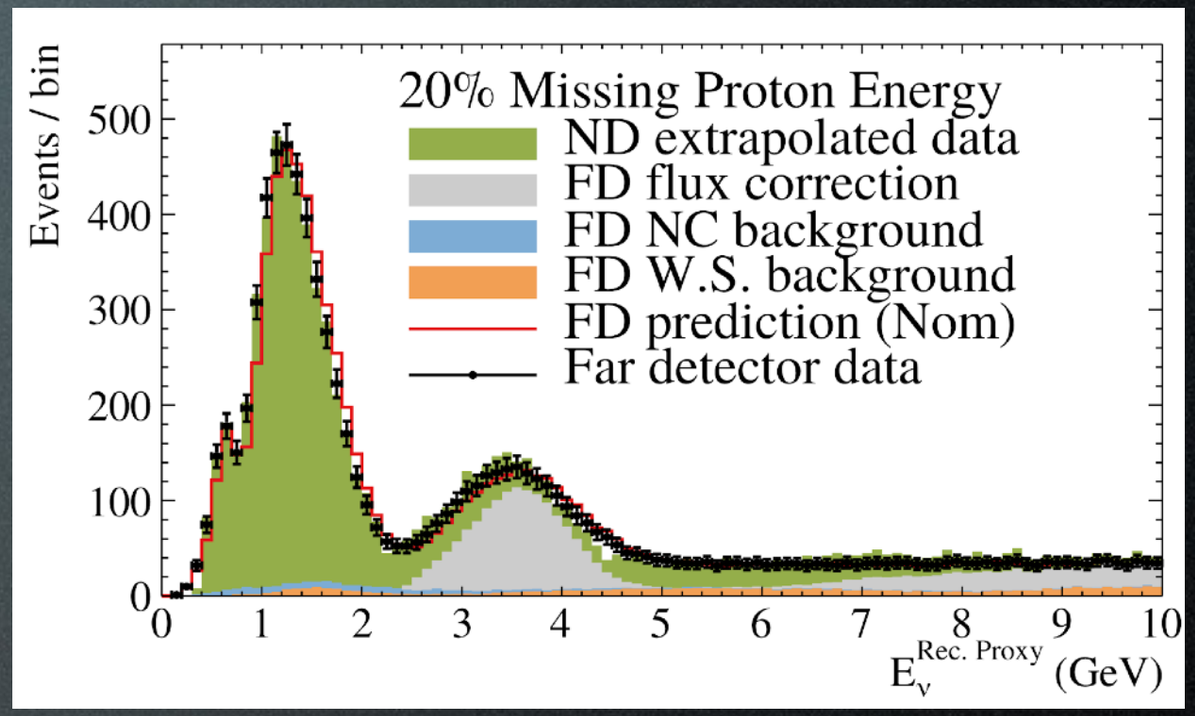




- Subtle mistakes in our modeling of ν-Ar interactions on argon can produce large biases on neutrino oscillation parameters
  - Missing energy (e.g. neutrons) cause feed-down in E_{rec} vs E_{true}
  - Mismodeling the shape of this feed-down can cause biases
    - Understanding the detector uncertainties is also critical (e.g. in hadronic energy measurements)

DUNE-PRISM to the Rescue?





- DUNE-PRISM can provide strong constraints on ν-Ar interaction modeling
  - By measuring a continuously varying set of neutrino energy spectra, the E_{true} -> E_{rec} relationship can be constrained
- However, challenges still remain
  - Differences in detector efficiency and resolution between the ND (ArgonCube + Muon spectrometer) and FD still must be precisely understood
  - Since the FD is on-axis, DUNE-PRISM cannot sample higher energies to constrain high-E_ν feed-down (other strategies, such as changing the horn current are under investigation)
  - Uncertainties in the neutrino flux prediction must be well constrained (beamline geometry, wrong-sign backgrounds, etc.)

Advantages of Adding a WbLS Detector

- A WbLS detector provides several complementary features to the DUNE LBL program
  - A different (simpler?) target nucleus
  - Different detector systematic uncertainties (and coupling of detector modeling to cross section modeling)
  - Improved neutron detection
  - Good energy resolution
  - Fast timing
- In the era of systematics limitations (i.e. when a 4th detector would come online), providing extra constraints on systematic uncertainties will be a high priority

Theia LBL Sensitivity Studies

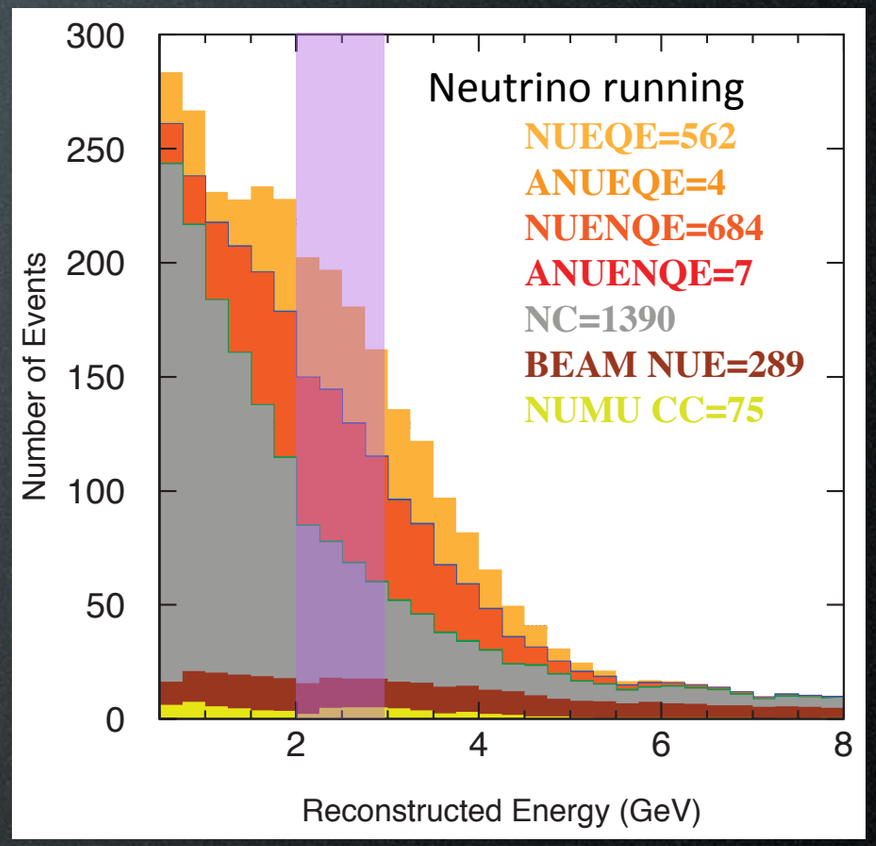
- The initial LBL studies have focused on a pure water (Cherenkov-only) phase
  - The additional benefits of WbLS have not yet been included (hadronic energy measurements, neutron tagging, etc.)
- Previous studies of a Water Cherenkov detector in the LBNF beam occurred in LBNE
  - These studies used older ("SK1") reconstruction tools and analysis techniques
- An updated set of studies has been conducted for Theia based on the latest Water Cherenkov analysis tools

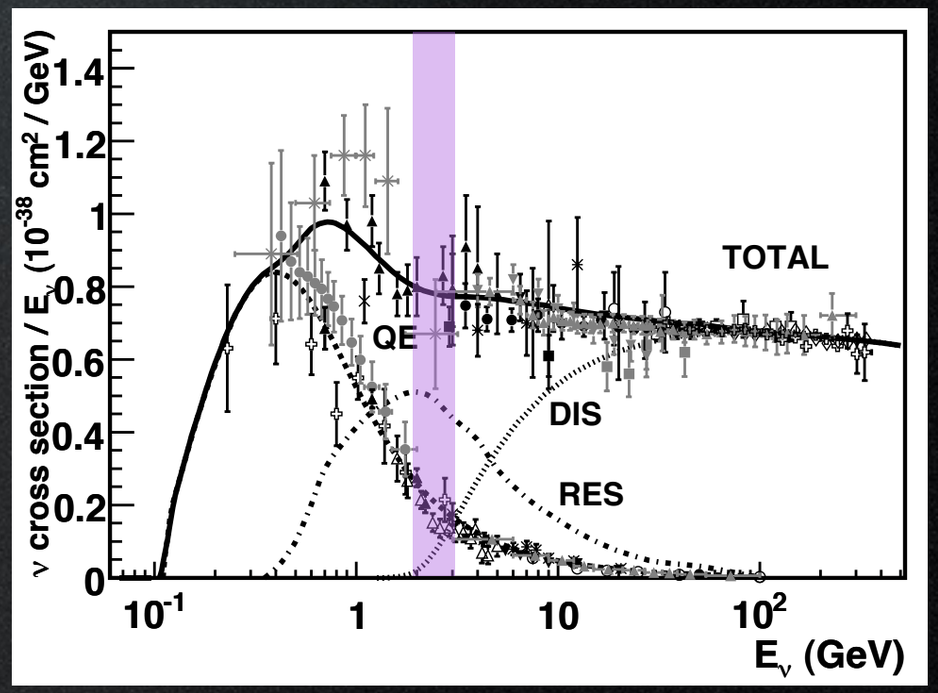
Reminder of LBNE Studies

- LBNF beam with a water Cherenkov detector at Homestake
- Prior studies (LBNE) made the following assumptions:

1. **Only single-ring events are selected** (~20% ν_e-CCnQE efficiency)
   - Largest interaction mode at DUNE energies of ~2-3 GeV is resonance (CCπ) events
2. **Neutral current** background rejection is based on **older reconstruction** tools (pre-FiTQun and even pre-POLFit)

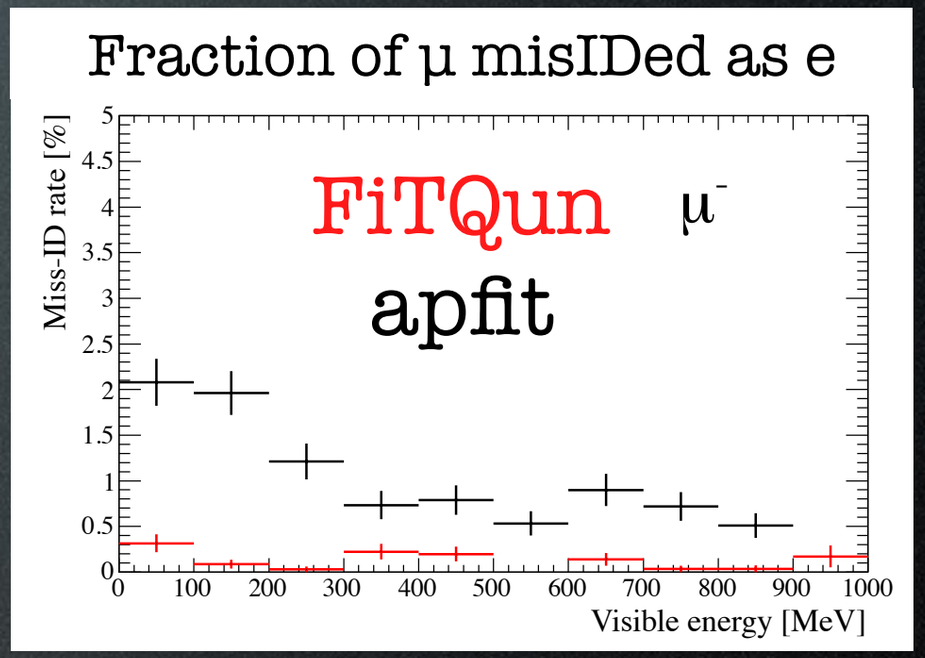
- Both of these assumptions have been revisited with updated reconstruction tools

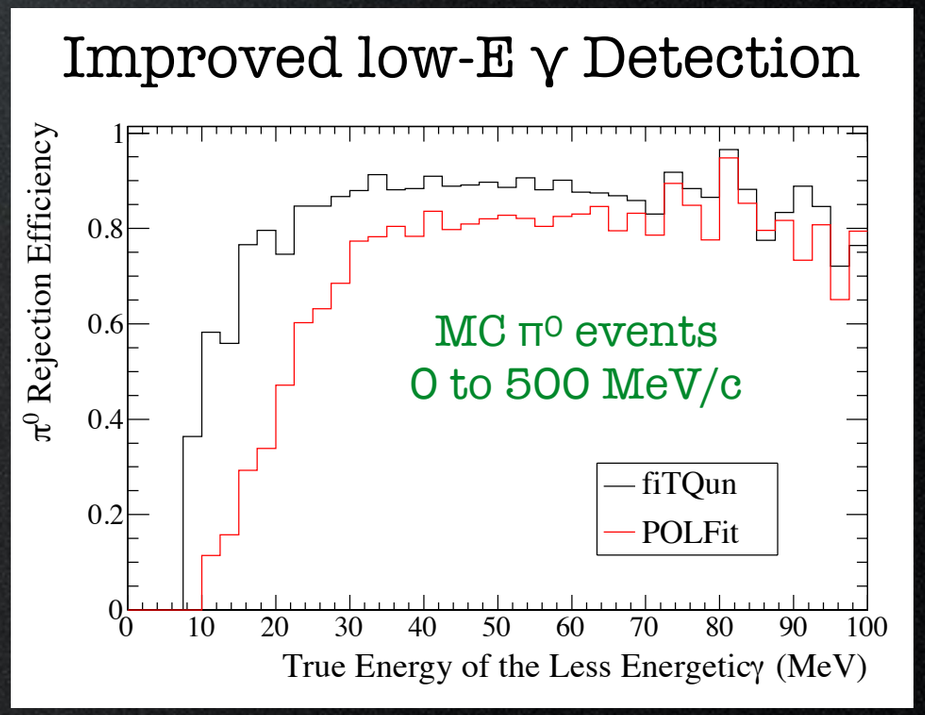




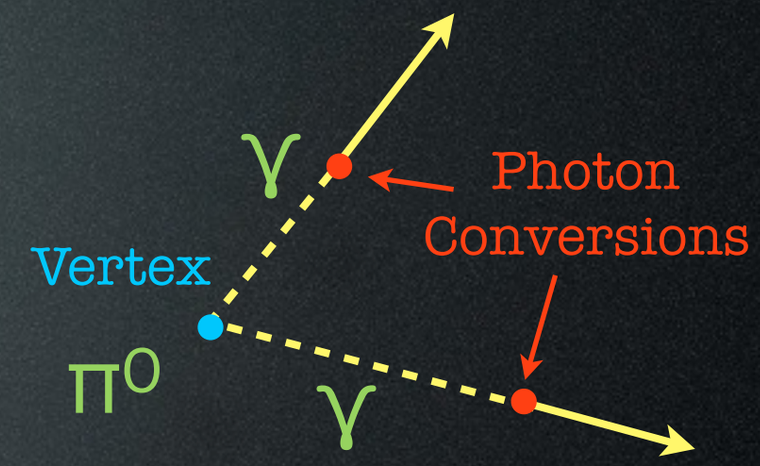
Advances in Cherenkov Reconstruction

- Since the LBNE WC studies, the FiTQun event reconstruction package has been implemented in T2K & SK
  - A likelihood-based fitter that generates charge and time PDFs for all PMTs for any proposed set of final state particles
  - Substantial improvements are seen in e/μ separation and NC (π^0) rejection
- FiTQun is now exclusively used for all T2K oscillation analyses, and in the latest SK atmospheric analysis
- FiTQun can naturally incorporate scintillation light, but this has not yet been implemented

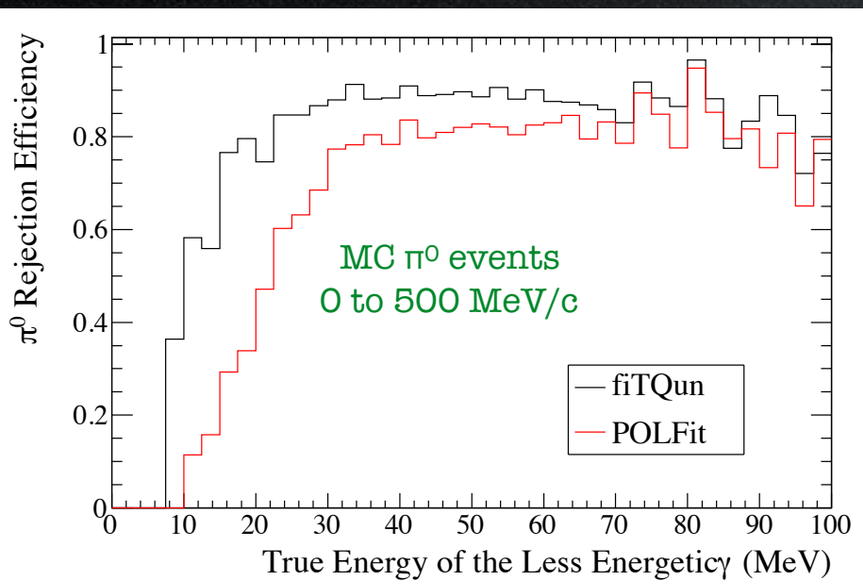


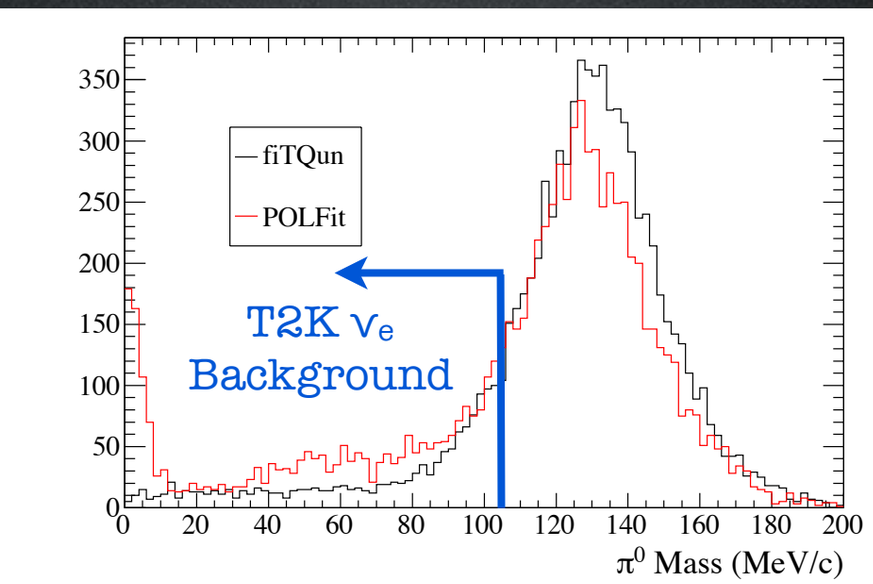


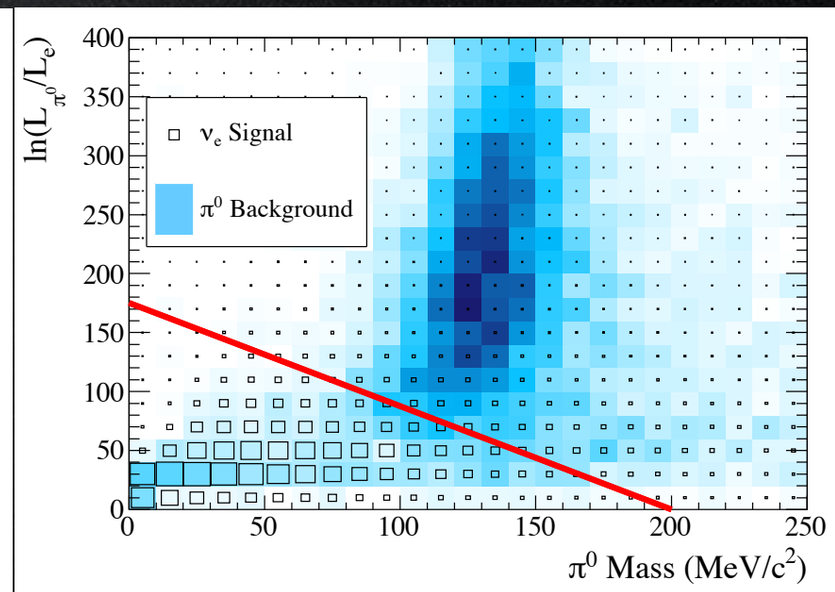
FiTQun π^0 Rejection



- **Goal**: identify a **low-E photon** in the presence of a **high-E photon**
- To reject π^0: Compare best fit likelihoods of π^0 fit & single-e fit (as a function of reconstructed π^0 mass)
- Large improvement in finding low energy 2nd ring
- ~70% reduction in π^0 background relative to POLFit (but not even POLFit was used in the LBNE studies)



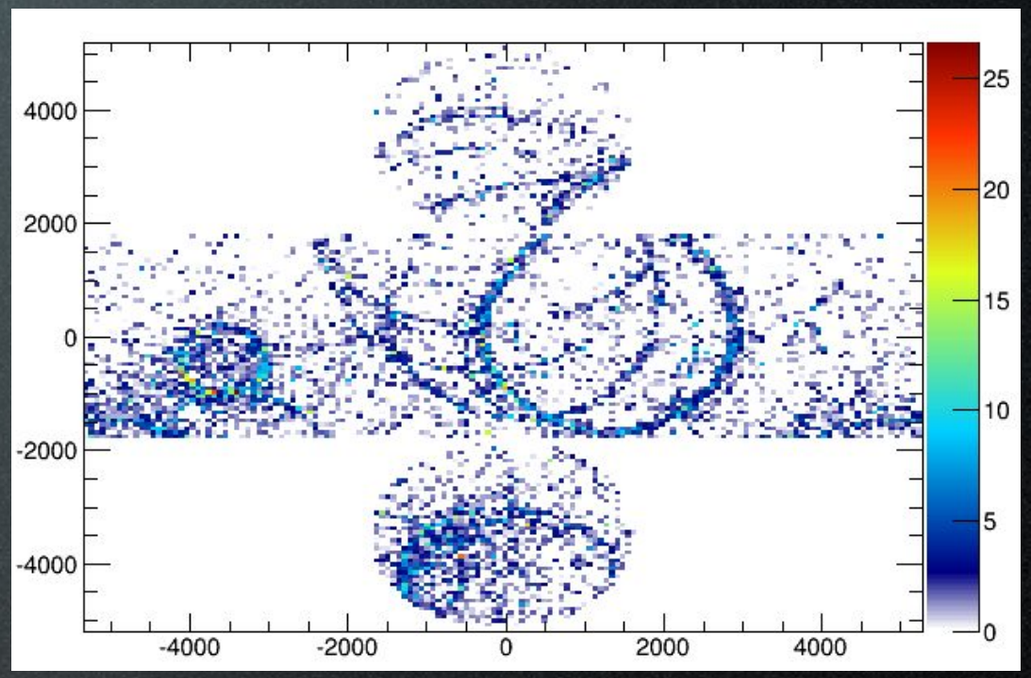


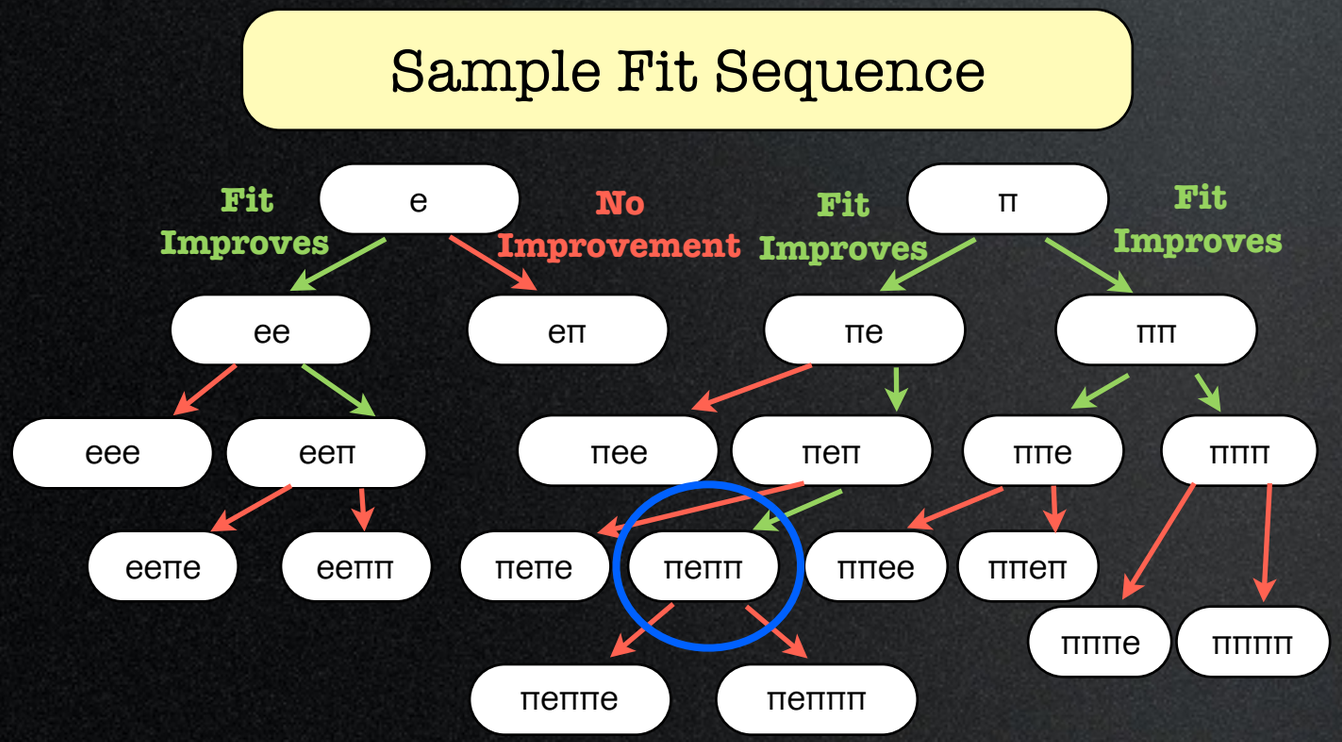


Multi-Ring Events

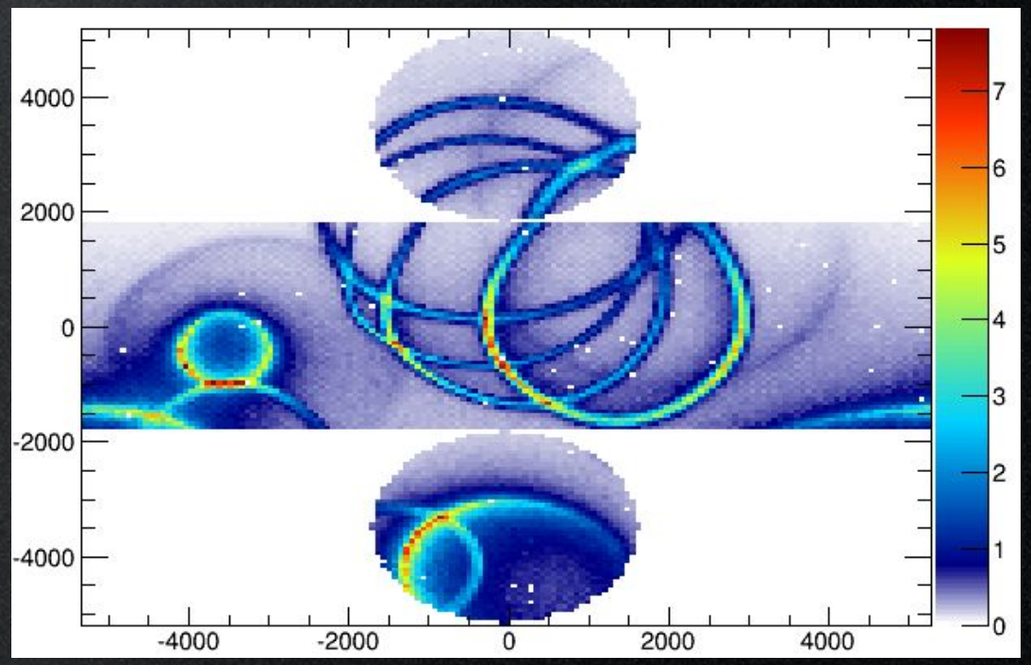
- FiTQun can currently reconstruct up to 6 rings in a staged approach
  - Each step sequentially adds a “track-like” (π^+) or “shower-like” (e) ring
  - The chain terminates when adding a ring does not sufficiently improve the fit
- Ring counting & PID are significantly improved

Hit Charge Distribution



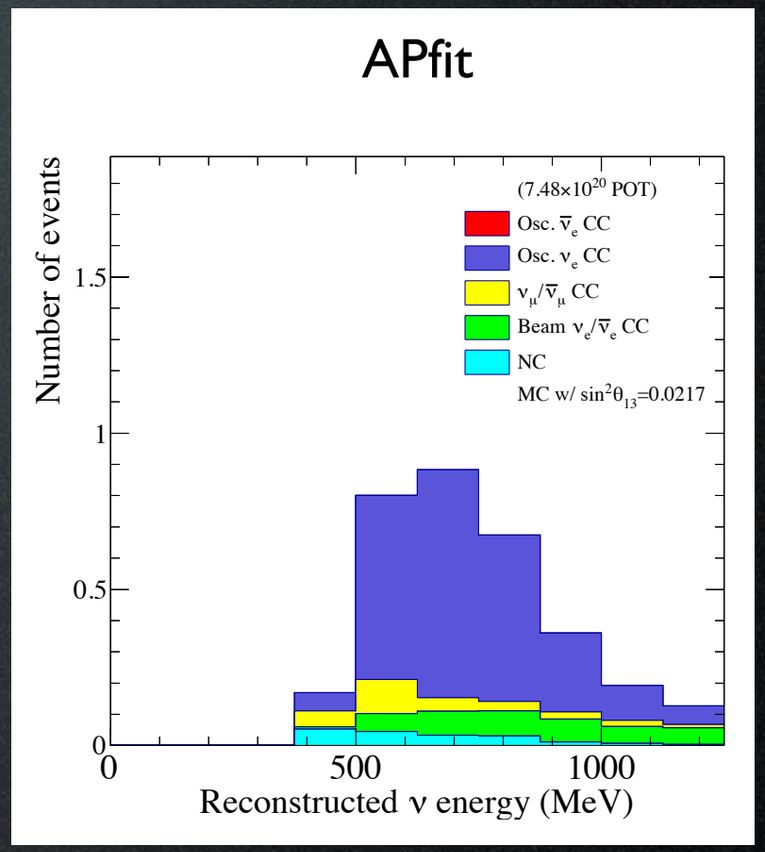


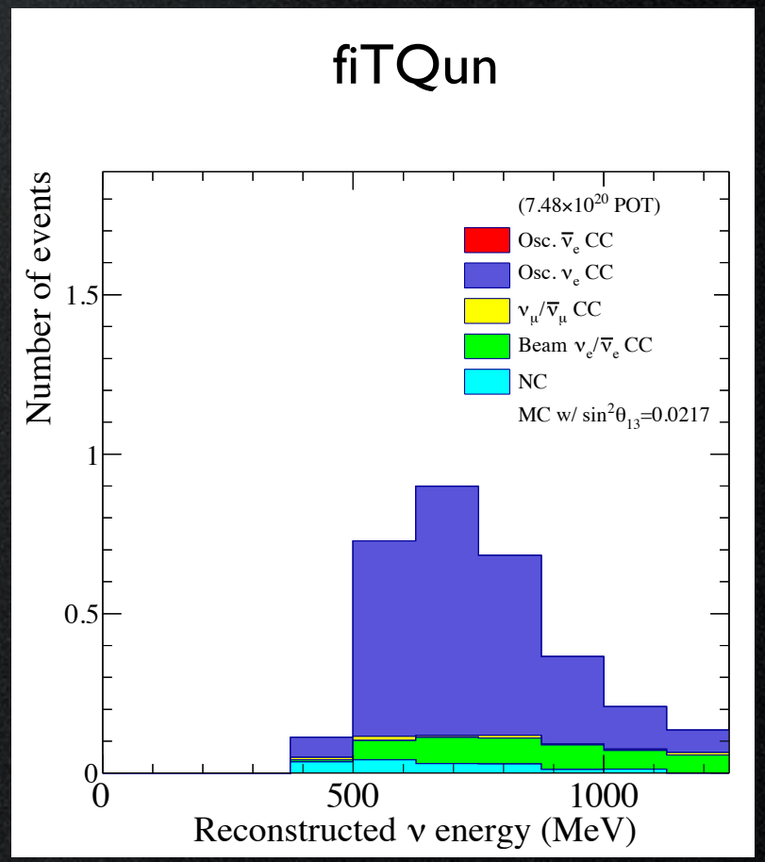
Reconstructed “Mean” Charge



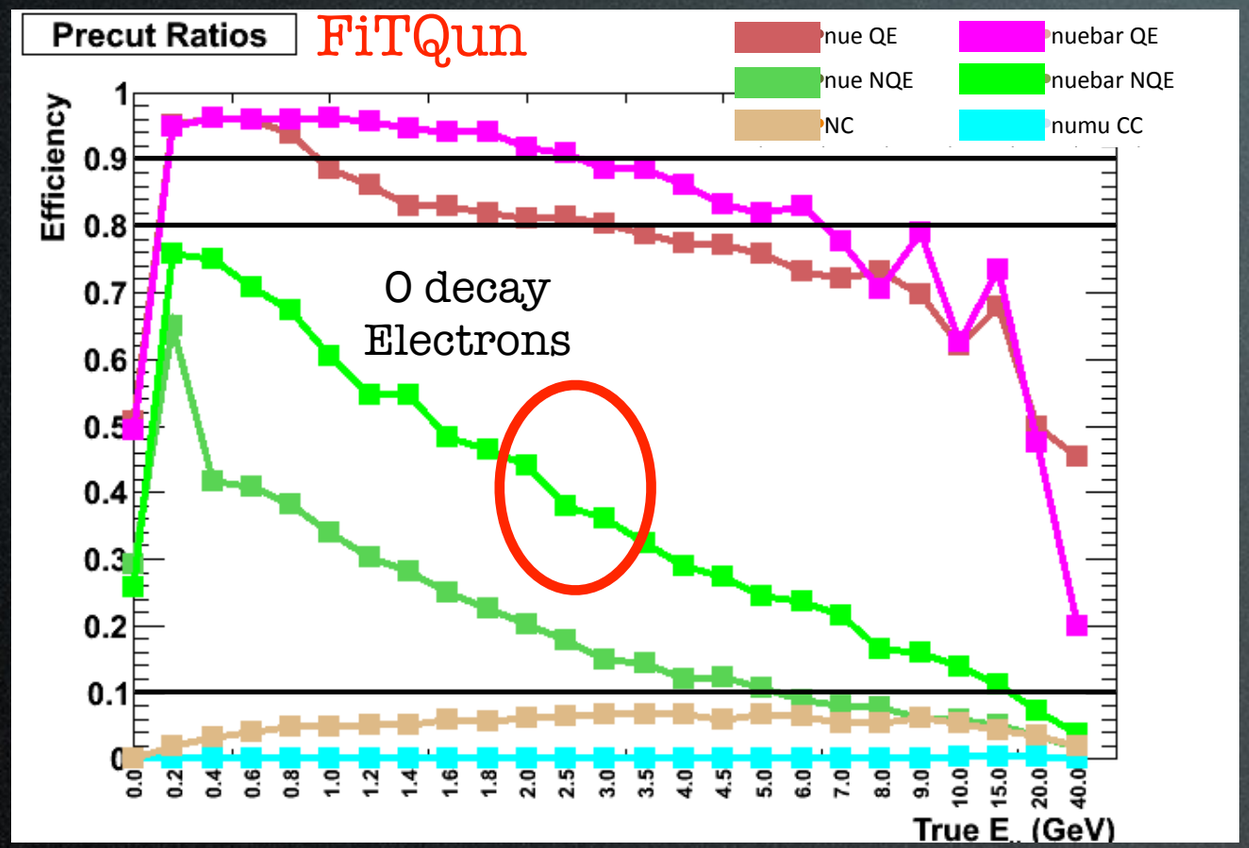
"1-Ring" ν_e-CCπ^+ in T2K

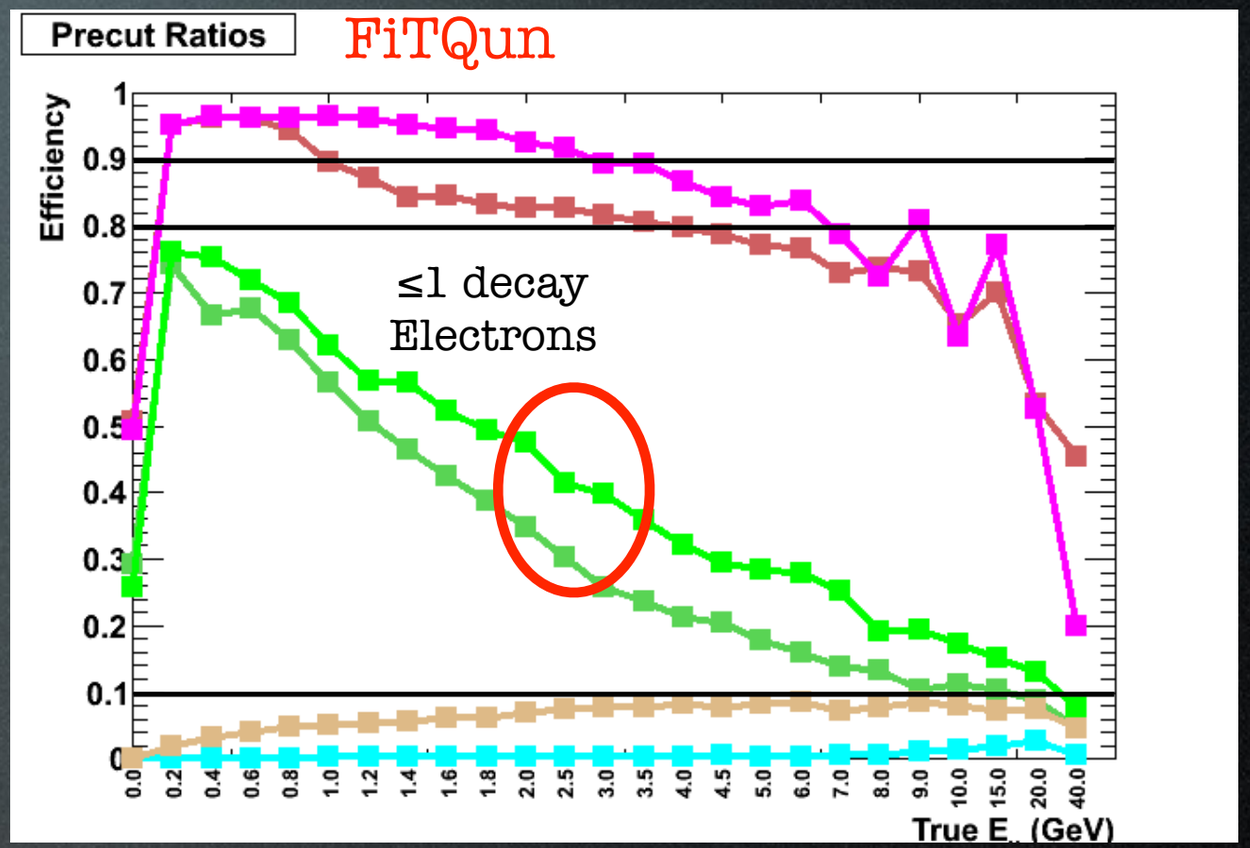
- The newest T2K ν_e sample is ν_e-CCπ^+ where the π^+ is below Cherenkov threshold
  - Still a 1-ring event, but with a Michel electron
- Previously, these events were contaminated with ν_μ-CC background
  - Improved e/μ separation now allows for a high purity 1-ring, 1-Michel ν_e selection
- Eventually, Theia may have a better tag of below Cherenkov pions via scintillation (if separable from protons, etc.), but this is not yet included





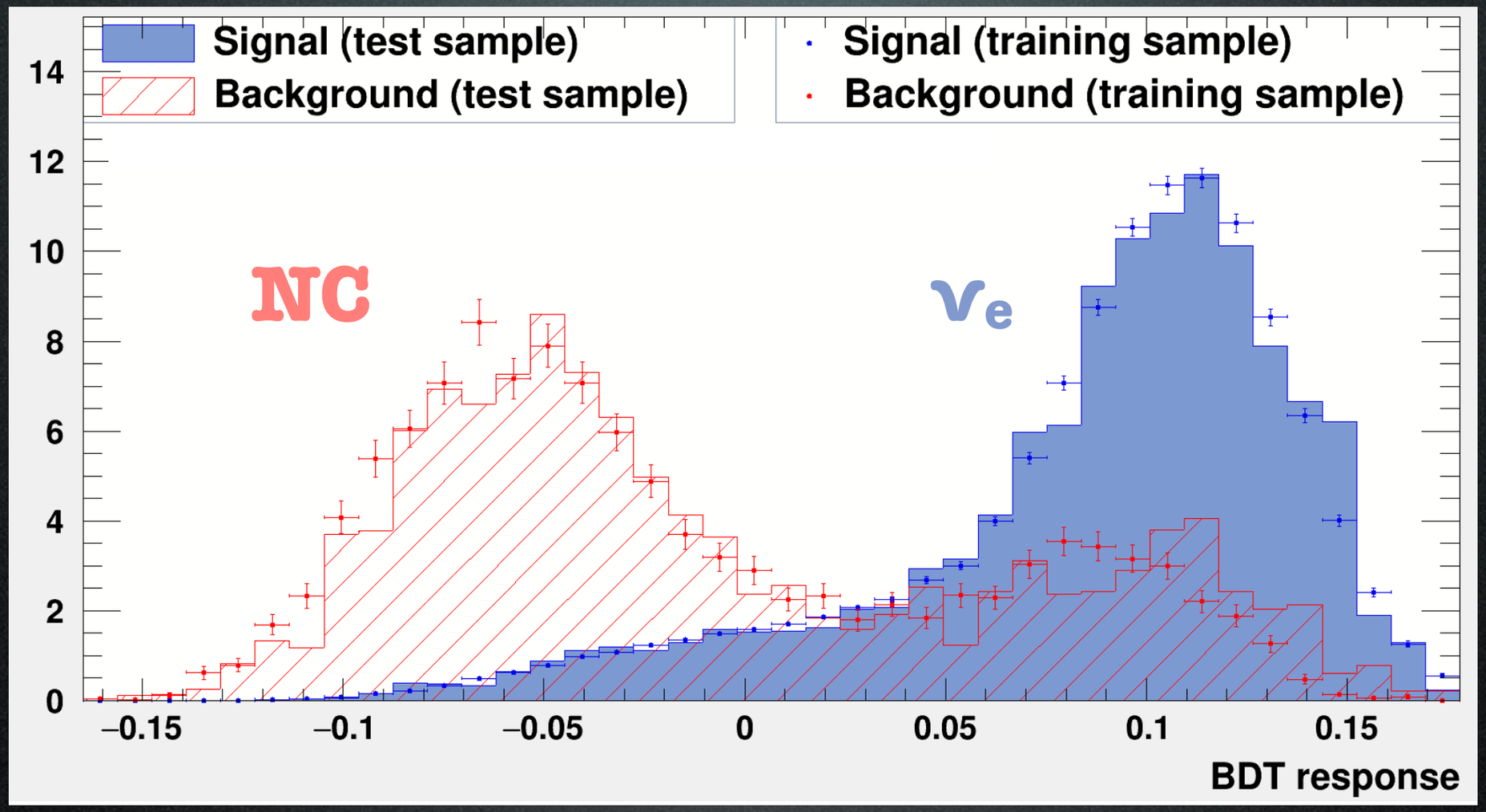
Theia ν_e Samples (0 vs 0+1 Decay-e)





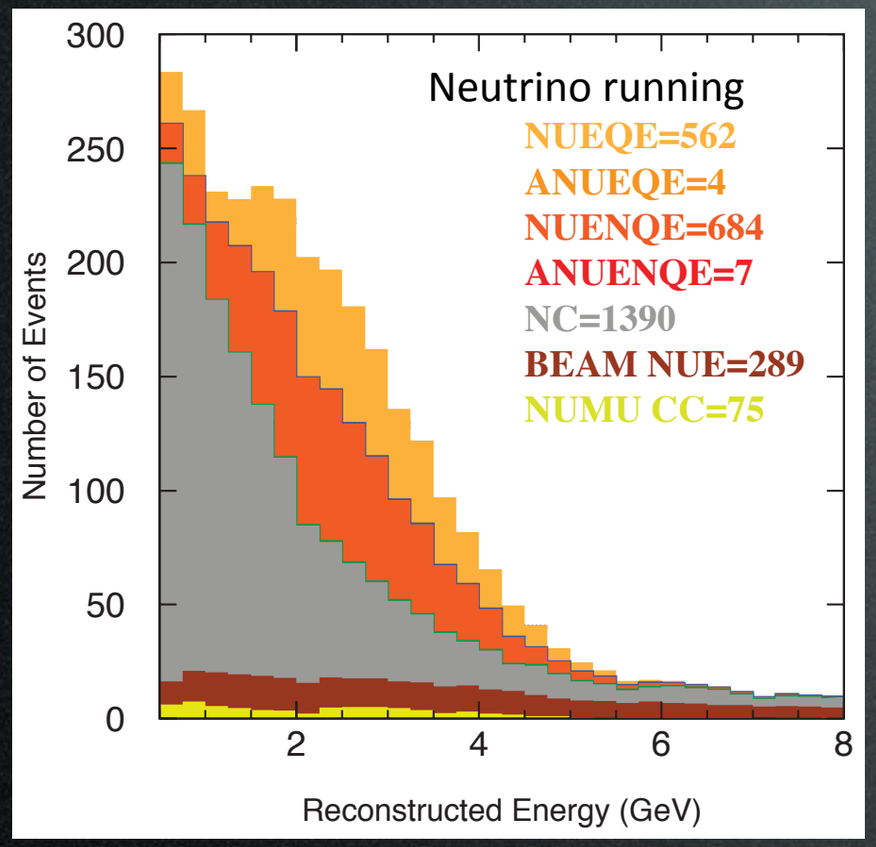
- By adding in the new "1-ring" CCπ^+ sample, we see a very large gain in ν_e CC non-QE efficiency
  - More than 50% increase in the 2-3 GeV region
  - These events have the largest cross section at the DUNE oscillation maximum

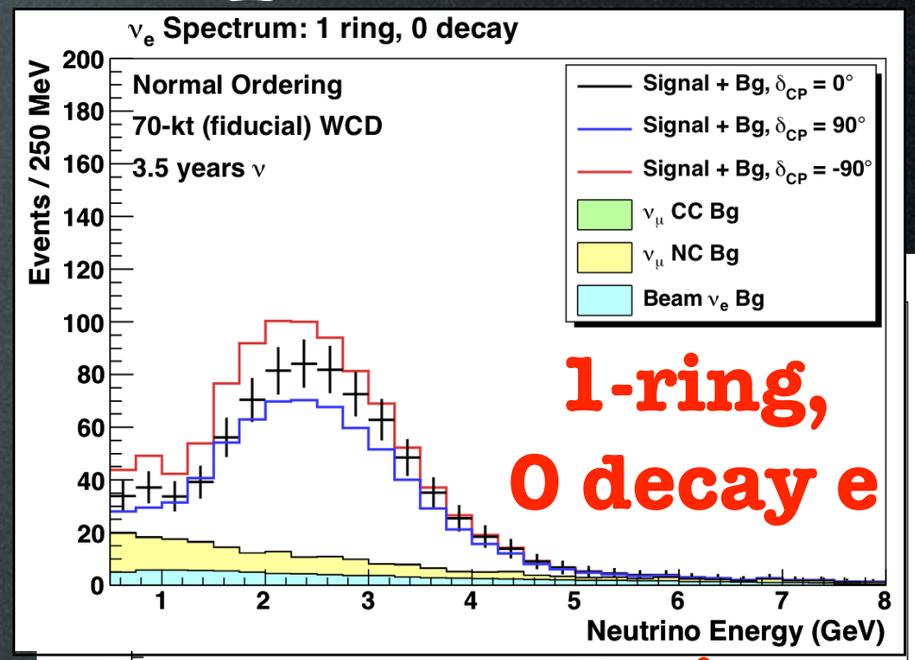
Boosted Decision Tree π^0 Cut

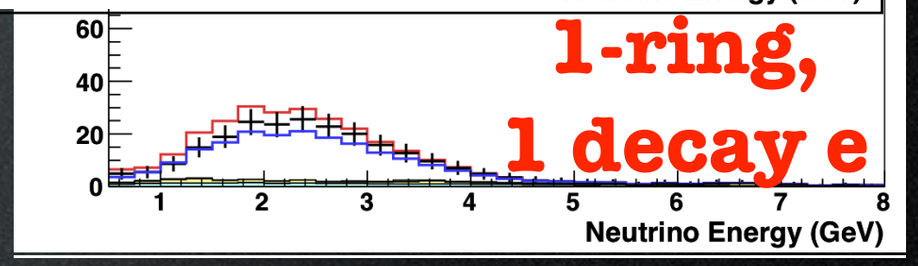


- The best-fit likelihoods and reconstructed kinematics of the multi-ring fits were combined into a boosted decision tree
- The primary goal of this cut is to remove neutral current (π^0) background (as in the LBNE analysis)

1-Ring Event Samples

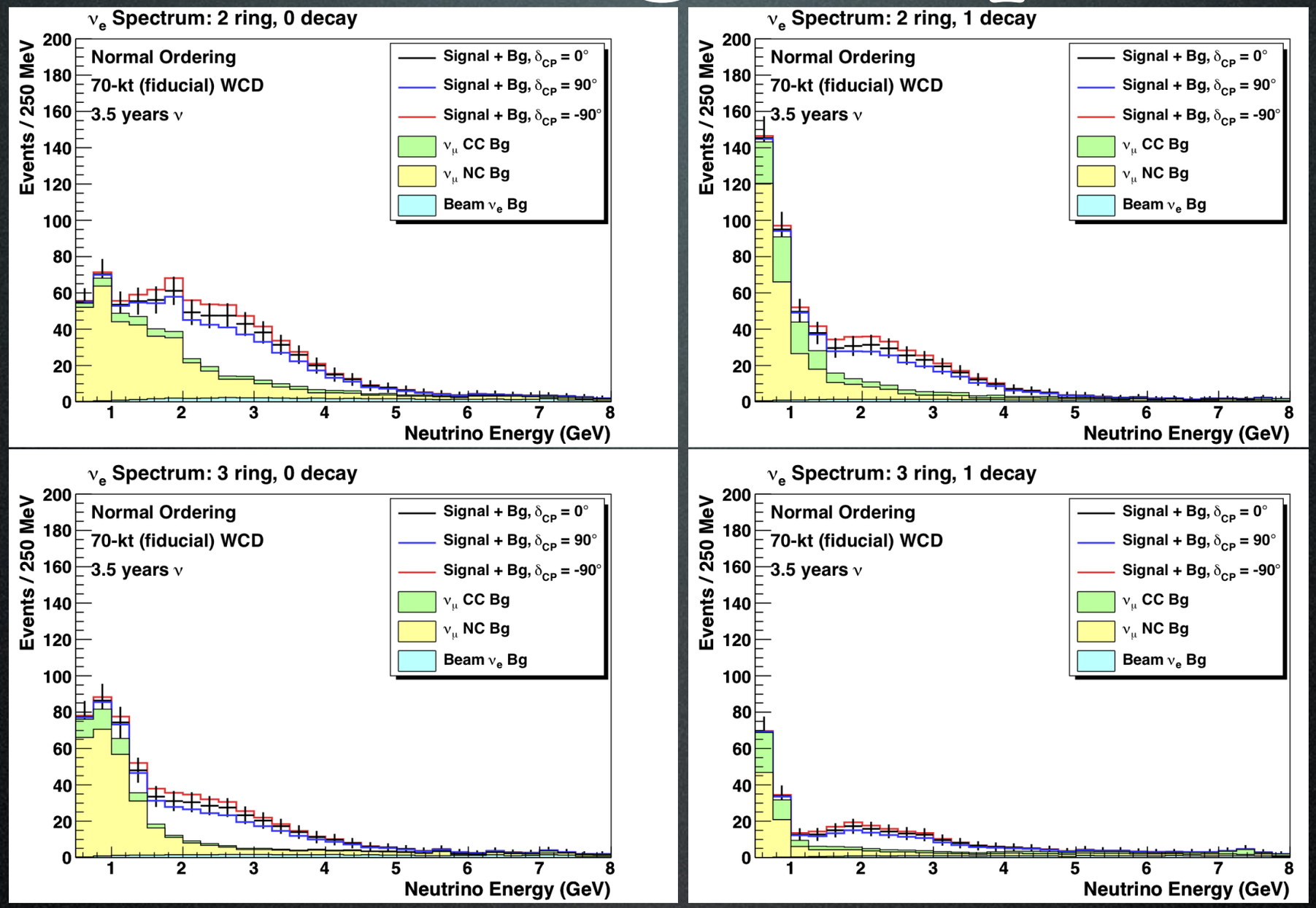






- The 1-ring, 0-decay-e sample has a substantially reduced NC background
- The new 1-ring, 1-decay-e sample increases the statistics by ~30%
  - The purity of this sample is also higher

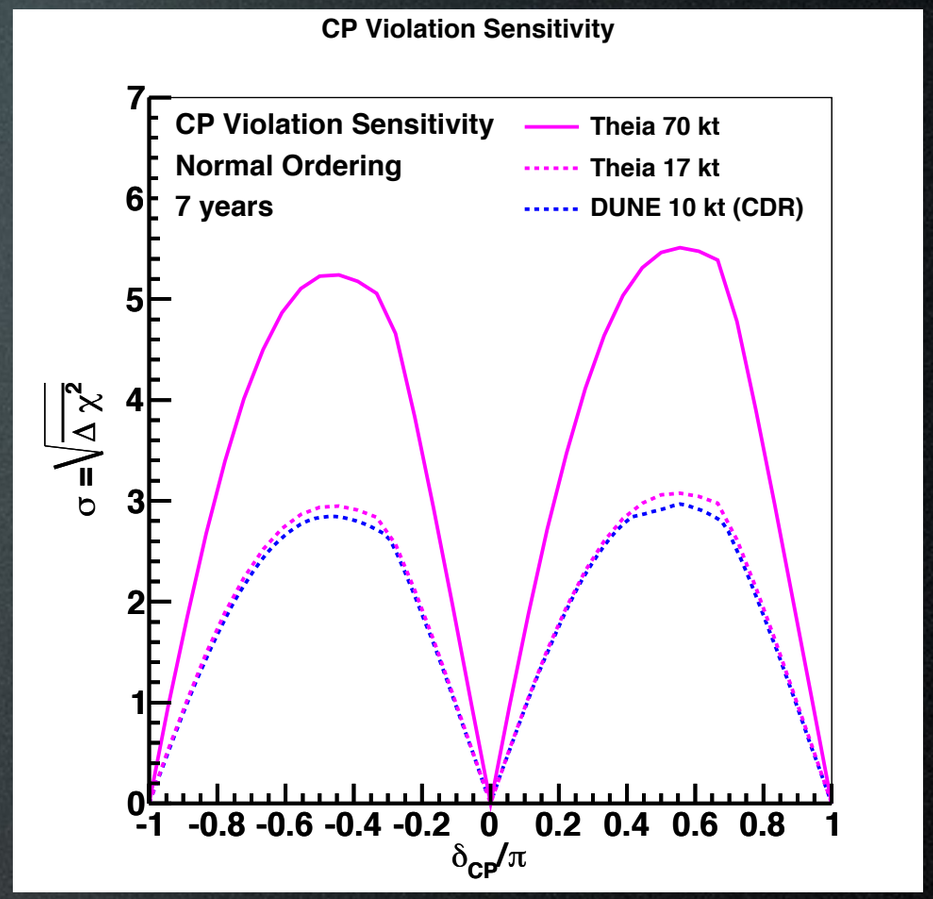
Multi-ring Samples

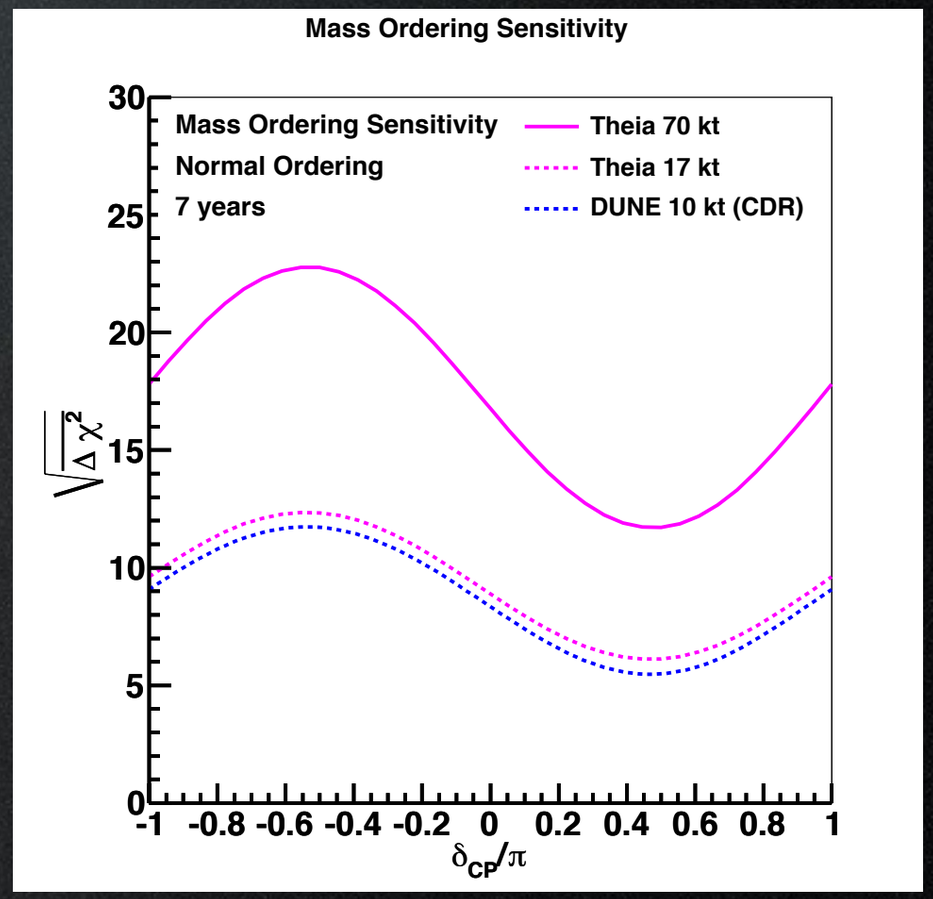


- Additional 2- and 3-ring samples also have controllable backgrounds
  - Selections have not yet been optimized for CP sensitivity

Sensitivity

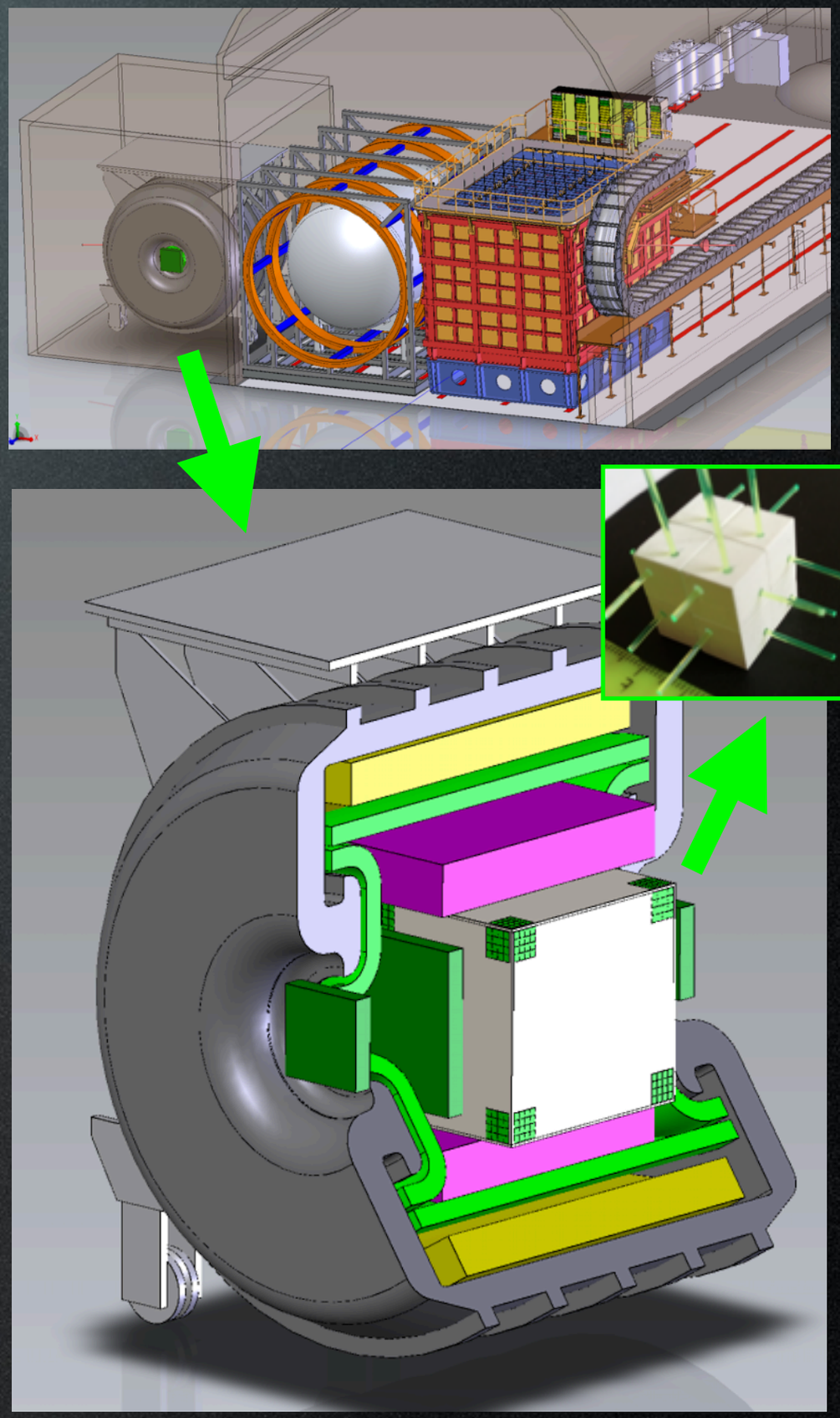
- Sensitivities produced with the same GLoBES framework used for the DUNE CDR analysis
  - Systematic assumptions are also consistent with the CDR (2% signal, 5% background, uncorrelated among all samples)
  - Theia disappearance samples are not included here (impact is minimal)
- Both the CP and mass hierarchy sensitivity are similar for a 10 kt LAr module, and a 17 kt Theia module





Role of the Near Detector

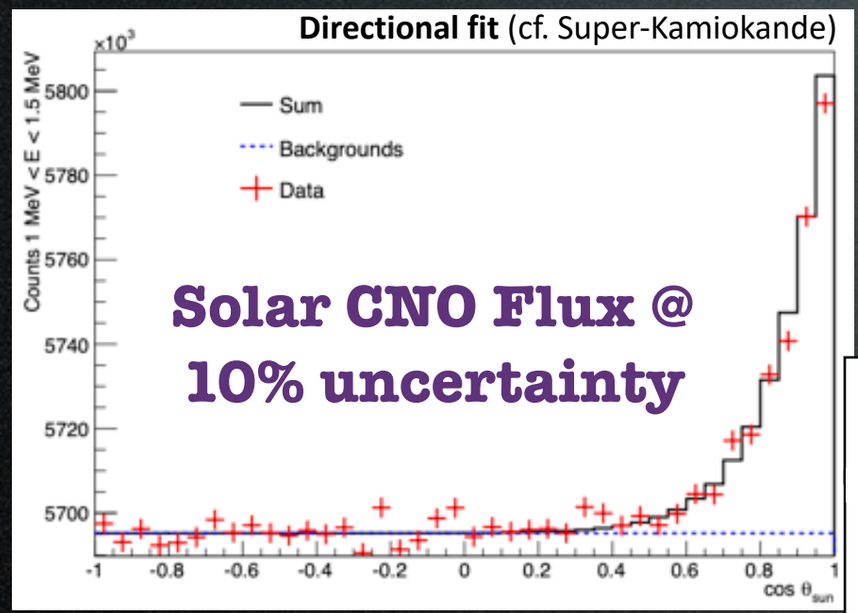
- DUNE will have a high granularity C target in the near detector (3DST)
  - This is the same detector technology that is being used for the T2K ND280 upgrade
    - The goal is to achieve 4π muon acceptance, and study short tracks near the vertex
- Similar to T2K, the 3DST could provide strong LBL constraints for Theia
  - Several possibilities exist to add water or WbLS targets in the 3DST as well

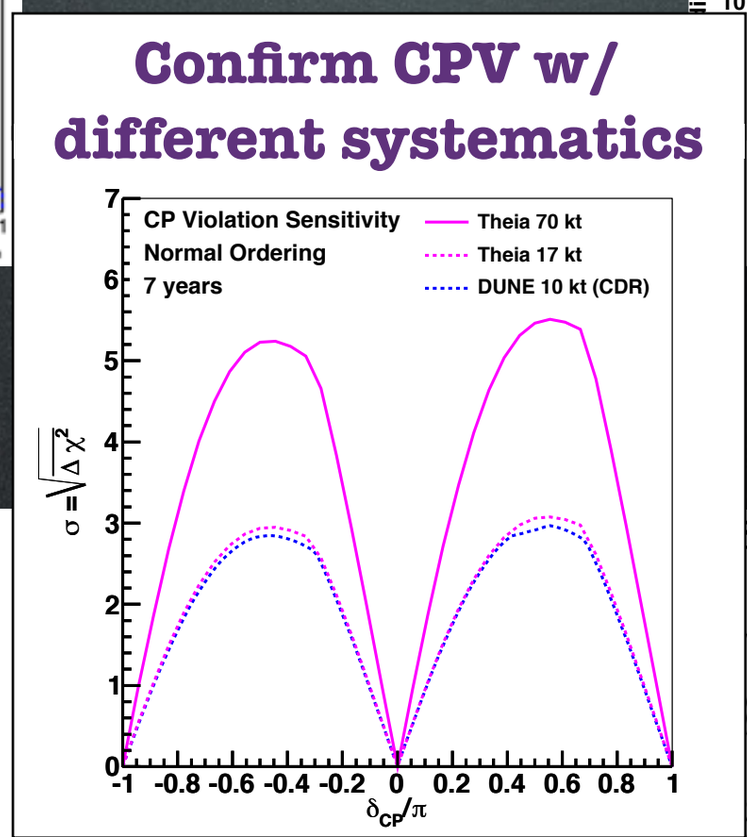


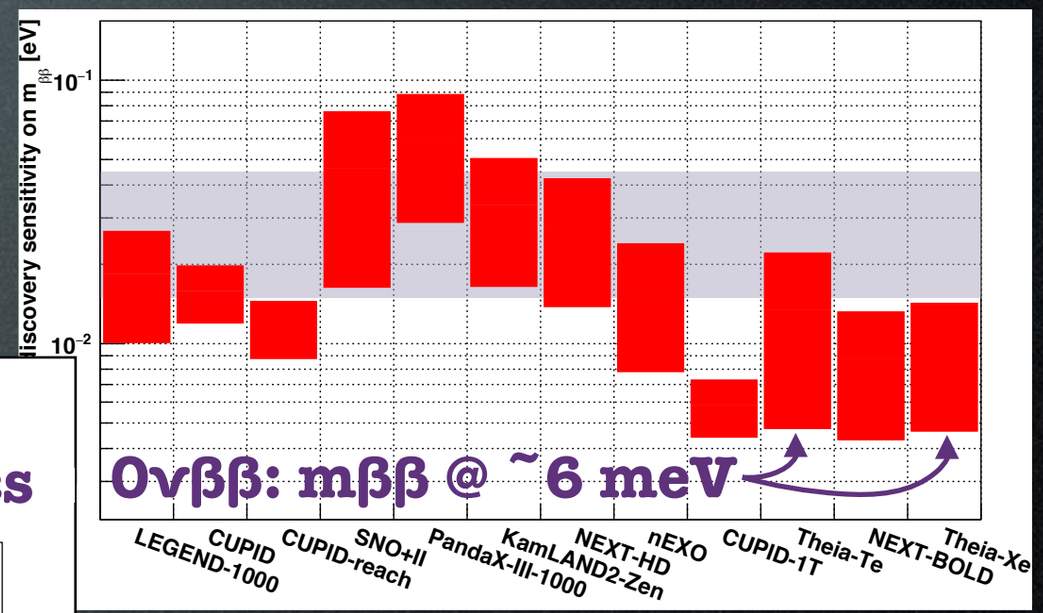
Summary I

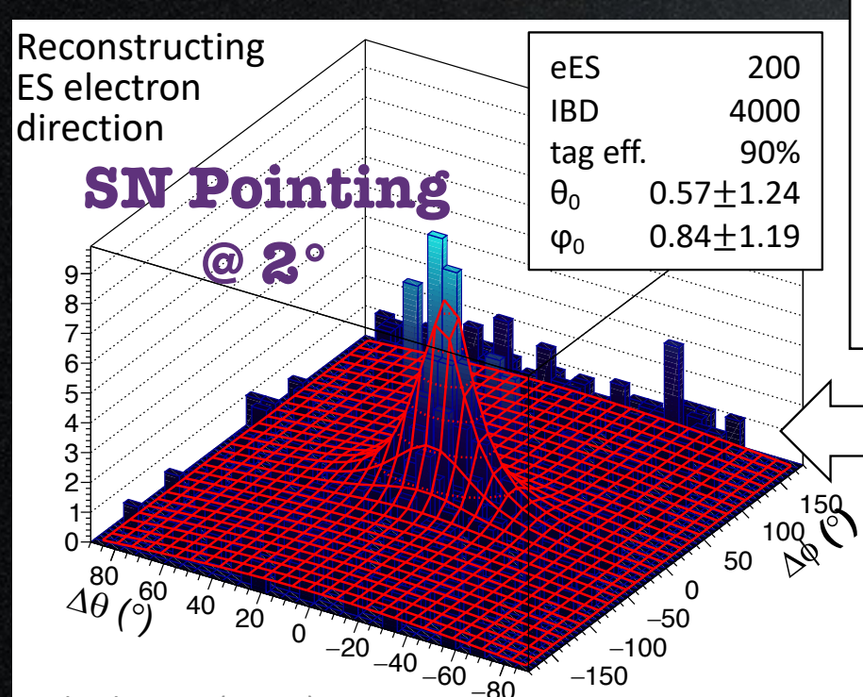
- Theia provides a set of LBL events that are complementary to the LAr samples
  - Different nucleus, detector systematics, neutron detection, energy resolution, timing, etc.
- Advances in Water Cherenkov reconstruction techniques provide substantial improvements over the those assumed in LBNE studies
  - Improved reduction of NC background and the addition of new multi-particles samples have substantially improved the CP sensitivity of a water-based detector in the LBNF beam
- A 17 kt Theia module can provide similar sensitivity in both CP & MH to a 10 kt LAr module
  - This does not include any improvements from the scintillation light Theia would provide
- Many opportunities for many aspects of such a detector (optical configuration, DAQ, electronics, calibrations, slow controls, etc.)

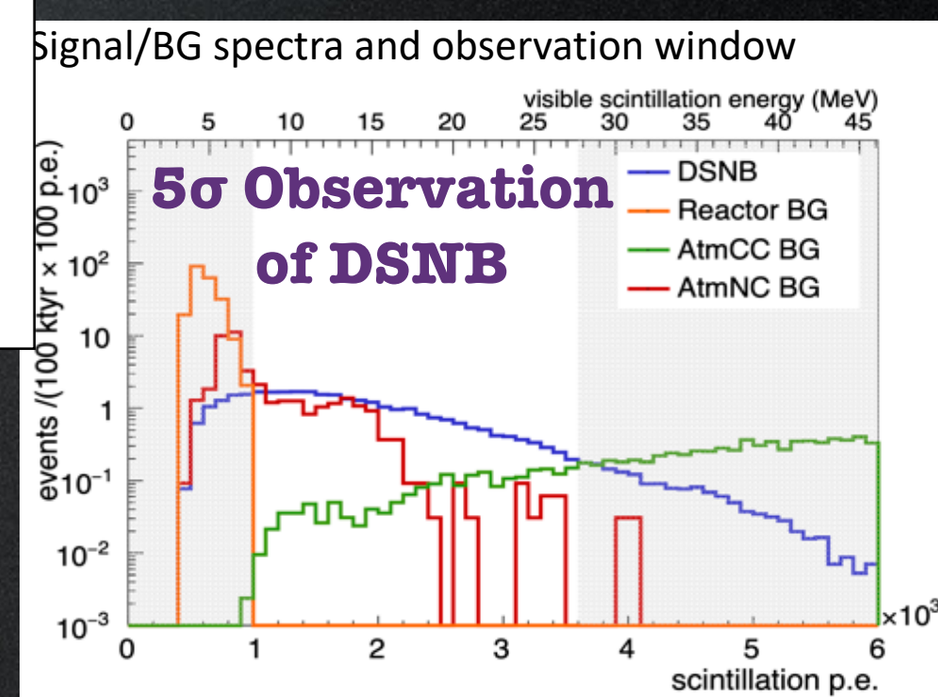
Theia can enhance the LBL program, and expand DUNE's physics reach!





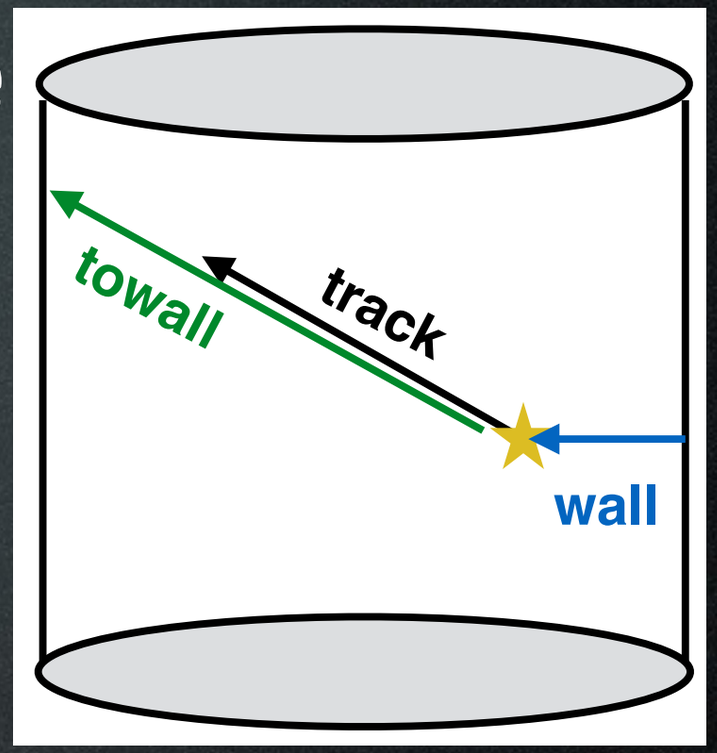
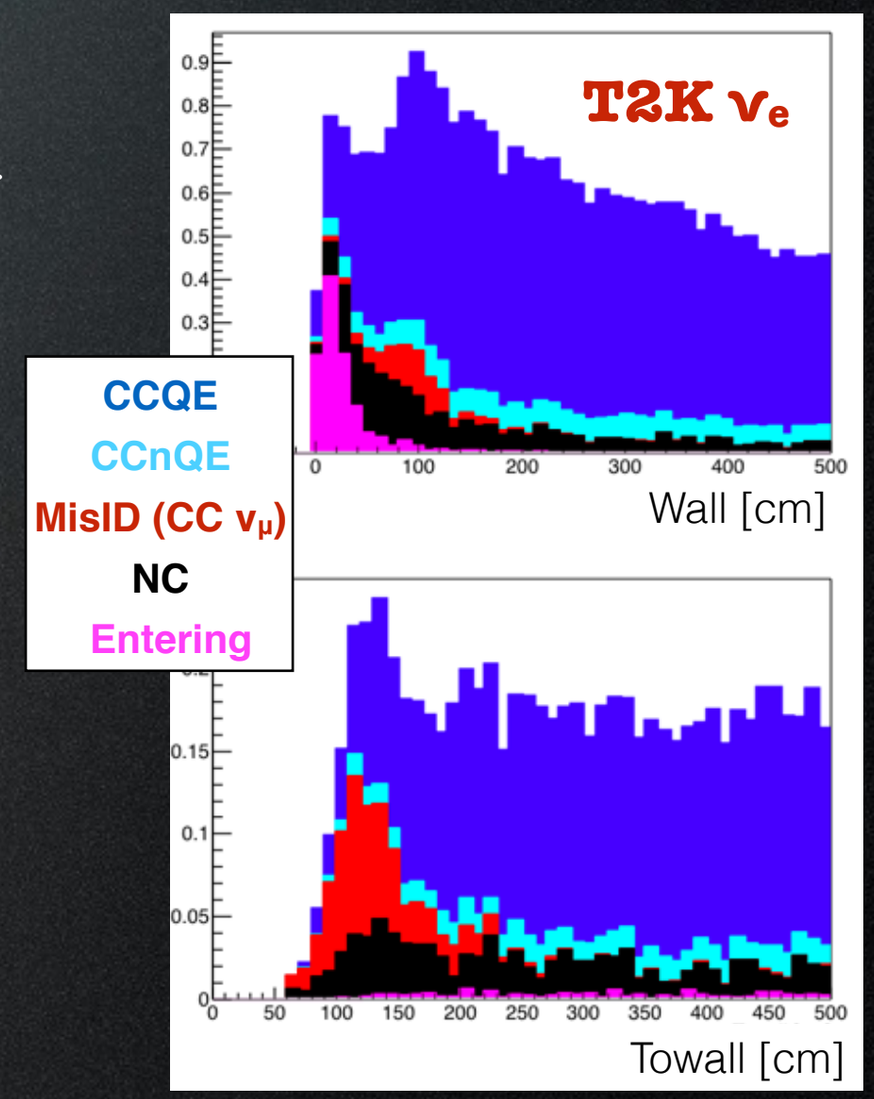






Supplement

Increased Fiducial Volume



- Previously in Super-K, event vertices required "wall" > 2 m
- The T2K event selection is now based on "wall" and "towall"
  - An event with small "wall", but large "towall" can be perfectly well reconstructed
  - Reconstruction performance degrades with small "towall", even if "wall" > 2 m
- New, expanded FV increases oscillated ν_e events by ~25%
- In the latest SK atmospheric analysis (2019), a wall cut of 50 cm was used, increasing the FV even further
  - This improvement has not yet been incorporated into the Theia analysis