THEIA Long Baseline Physics

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THEIA Workshop at UC Davis
April 13th, 2018

LBL Sensitivity Strategy

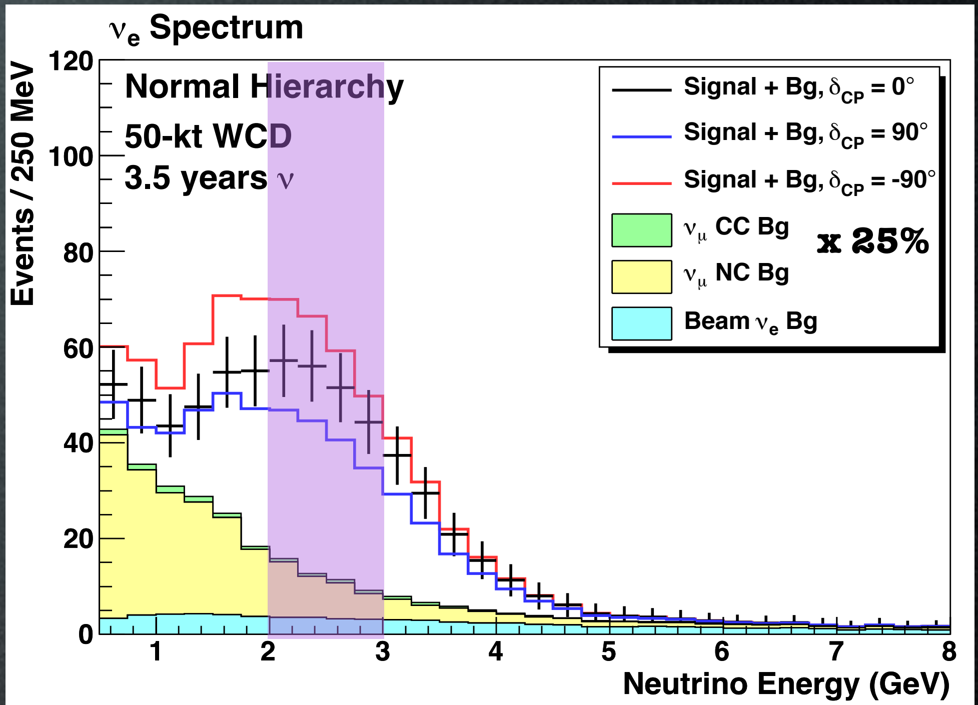
- Short term: Update LBNE water sensitivities based on last 10+ years of reconstruction improvements (FiTQun) and analysis updates
  - Sensitivities based on recent Super-K MC (just as LBNE studies)
  - Results are directly comparable to previous LBNE/DUNE sensitivities
  - WbLS is likely to be a small (negative) perturbation for LBL sensitivities
    - When we better understand how to reconstruct and utilize this extra information in the future, sensitivities may be further improved
- Unfortunately, we didn't quite complete step 1 for this meeting, but we are close, and recent progress will be shown today
- Longer term: Assess additional information that can be gained by WbLS (& faster photodetectors)
  - FiTQun has been adapted to run on (GEANT4-based) WCSim, and adapting it to also run on RAT-PAC should be straightforward
    - Original FiTQun mathematical formalism is based on MiniBooNE reconstruction (arXiv:0902.2222), and can naturally handle scintillation + Cherenkov light (with a bit of extra code work)
  - L. Pickard (UC Davis) is also made good progress on high-energy Cherenkov + scintillation reconstruction; additional collaboration may be useful

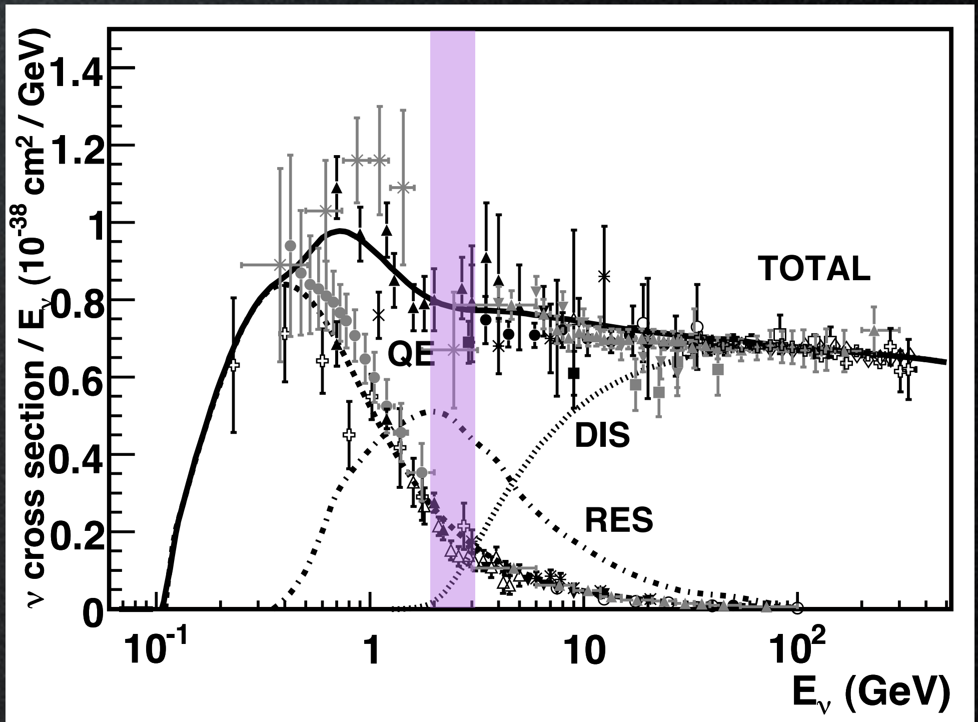
Reminder of LBNE Studies

- LBNE 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)

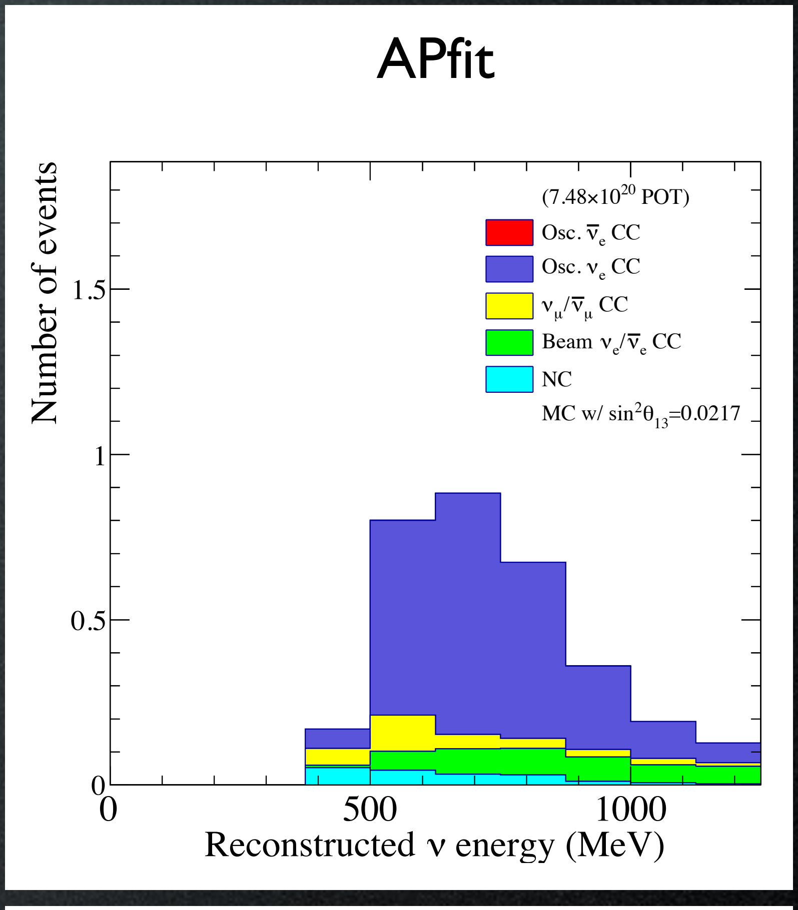
- Both of these assumptions are being revisited with updated reconstruction tools

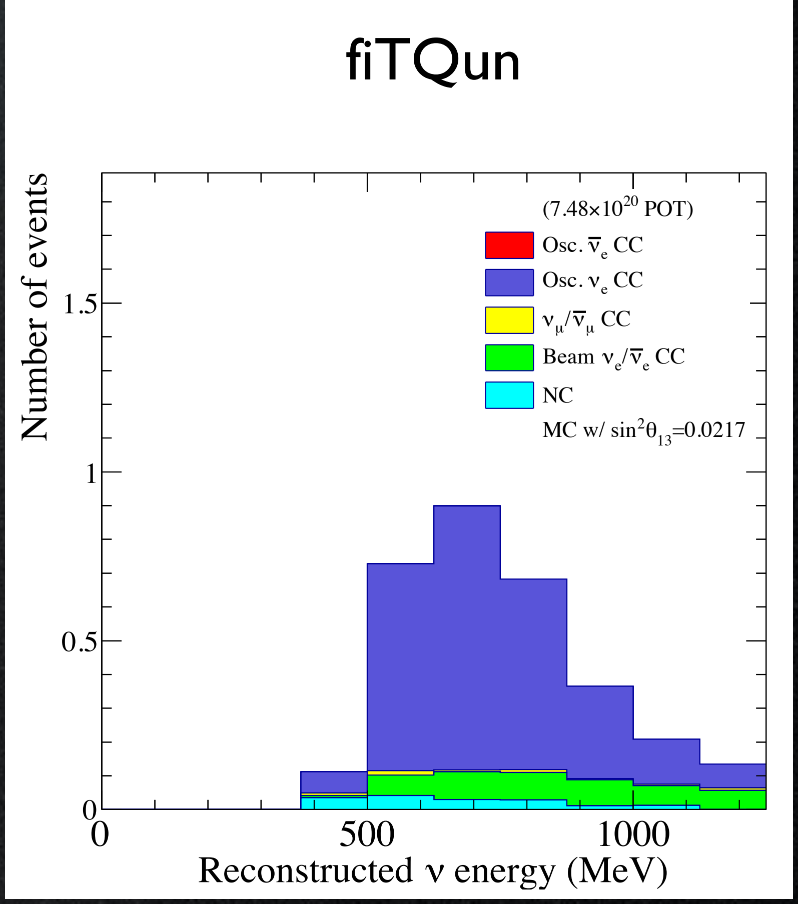




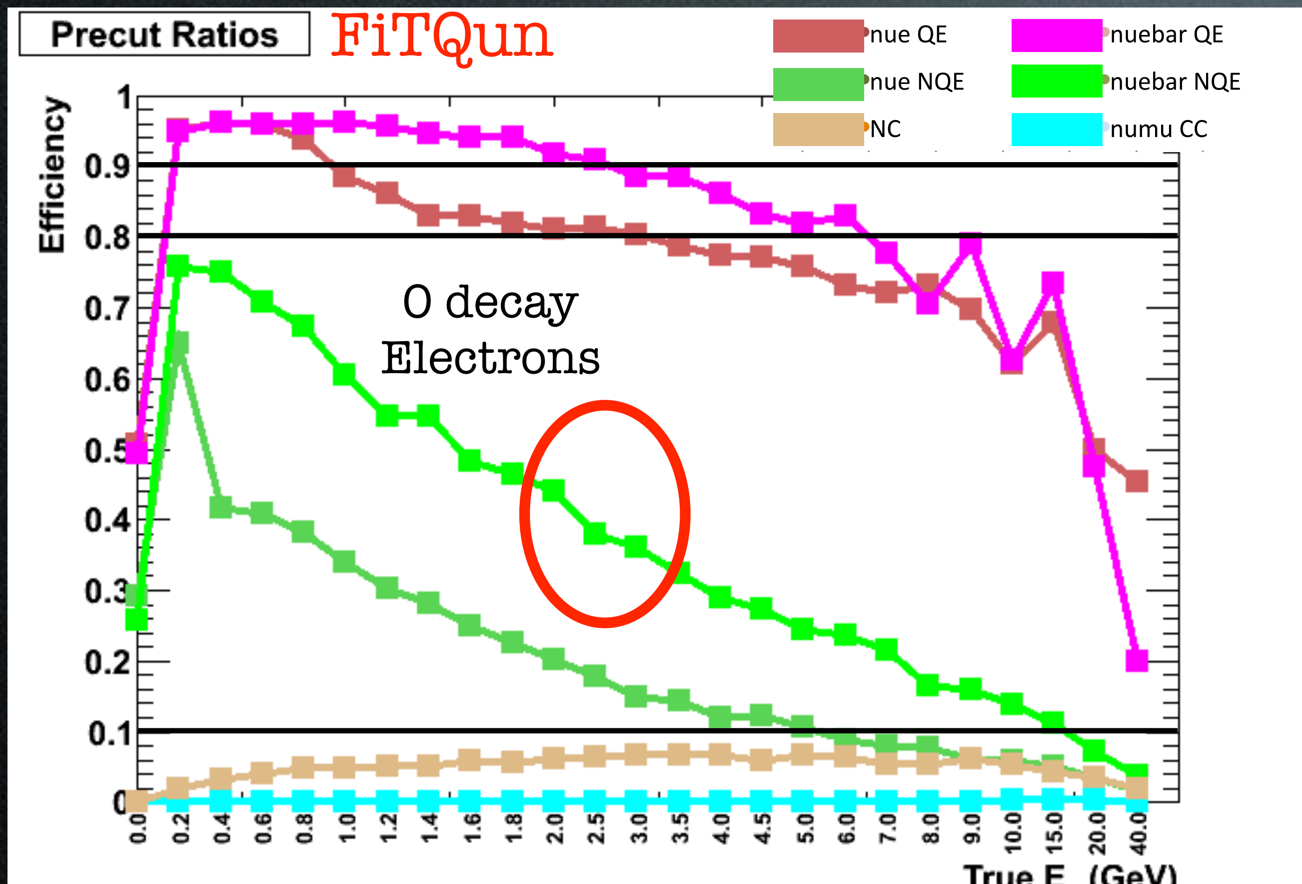
“1-Ring” ν_e-CCπ^+

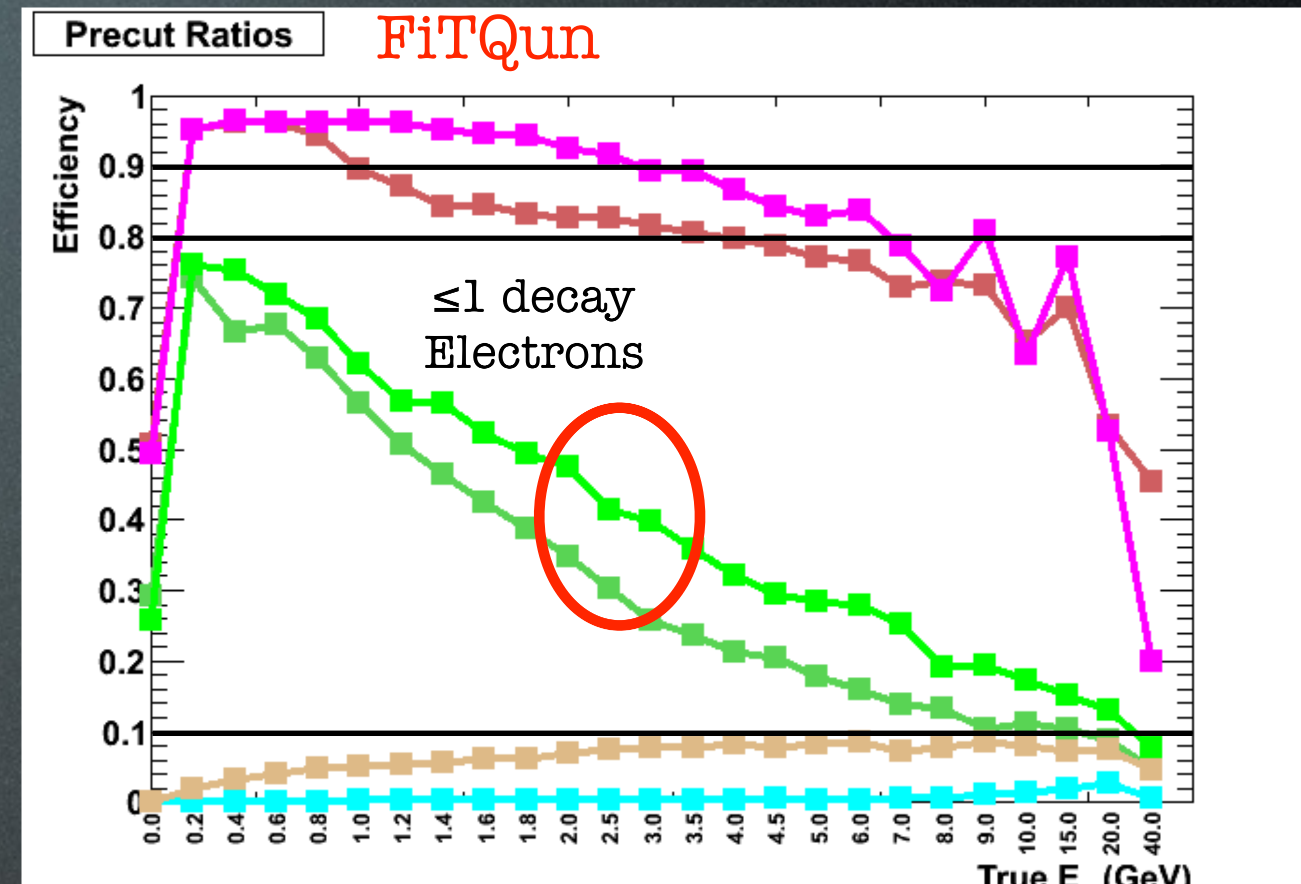
- A significant fraction of ν_e-CCπ^+ events at T2K have a pion below Cherenkov threshold
  - These are still ν_e appearance events and can be used for CP violation measurements
  - The π^+ can be tagged by the decay electron it produces (e-like ring delayed by ~2 μs)
- In previous ν_e selections at Super-K, 0 decay electrons were required to remove ν_μ background
  - FiTQun PID improvements no longer require this cut
- Eventually, in THEIA, we may have a better tag of below Cherenkov pions via scintillation (if separable from protons, etc.)



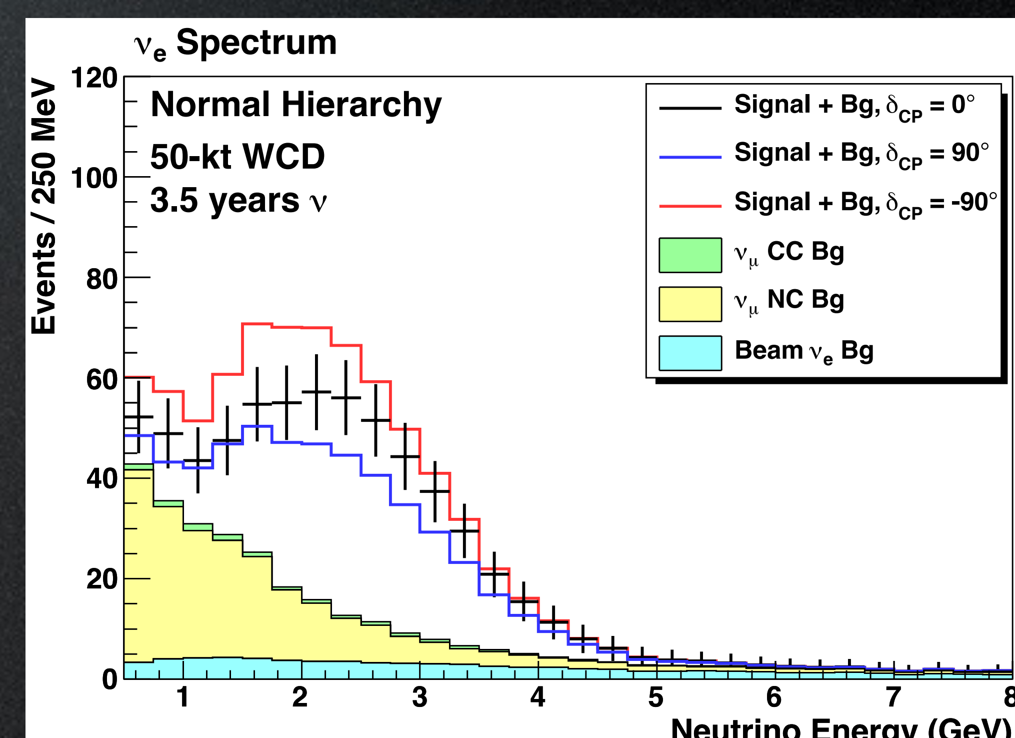


FiTQun 0 vs 0+1 Decay-e



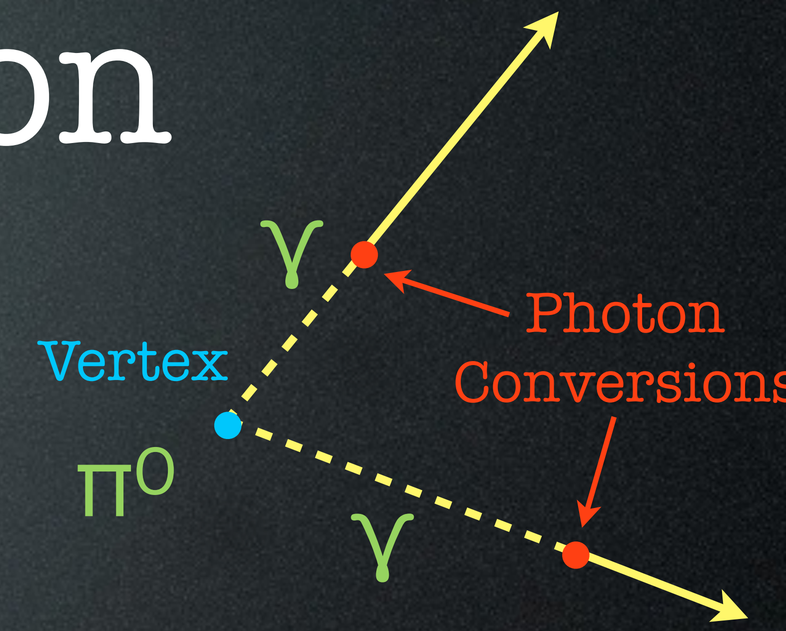


- By relaxing the zero decay electron requirement, can enhance the "1-ring" CCπ^+ events
  - Very large gain in **1-ring** ν_e CCnQE efficiency
  - These events have the largest cross section in the oscillation maximum
    - Efficiency is already increased more than 50% in the 2-3 GeV region

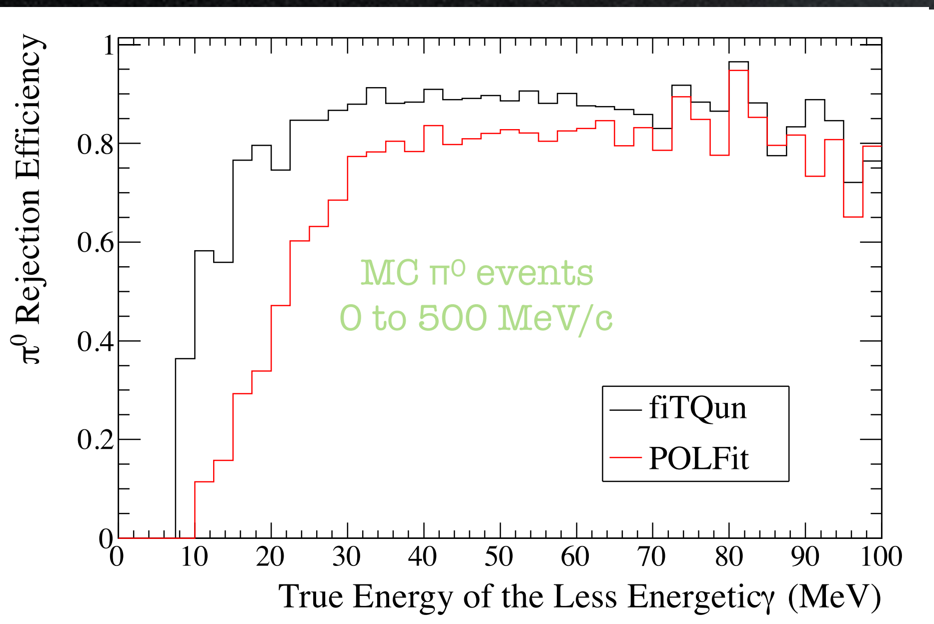


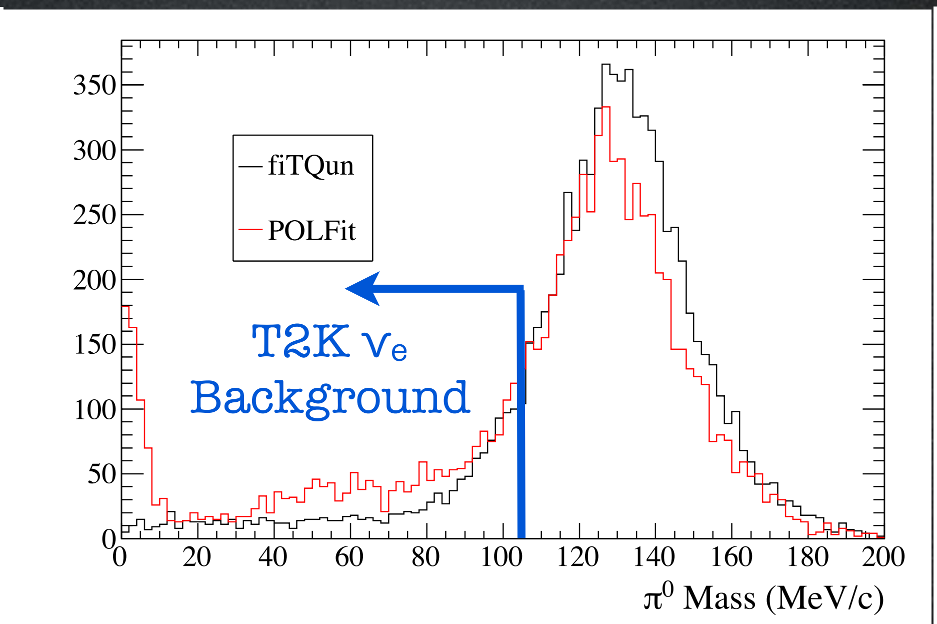
FiTQun π^0 Rejection

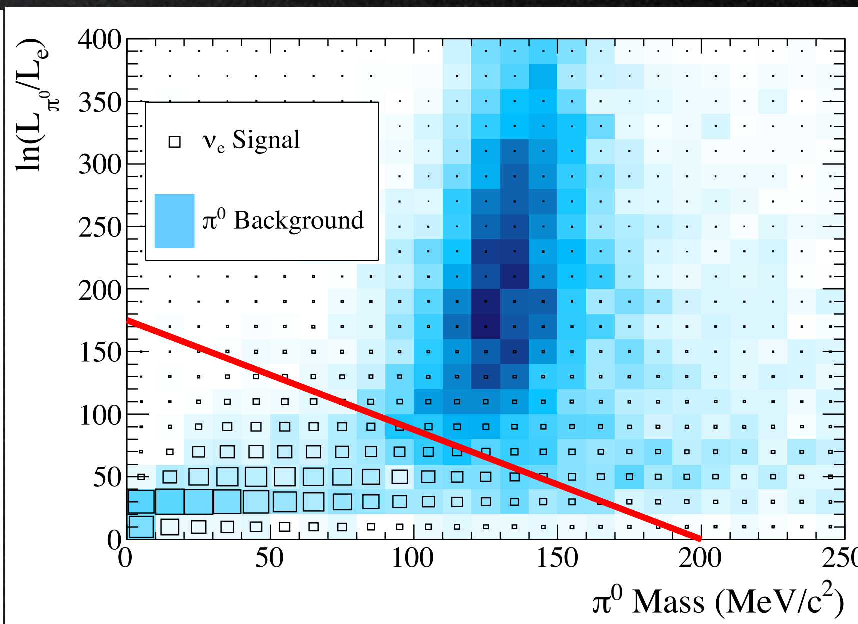
- Dedicated π^0 fitter with two electron/photon hypothesis rings produced at a common vertex (includes photon conversion lengths)



- 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)



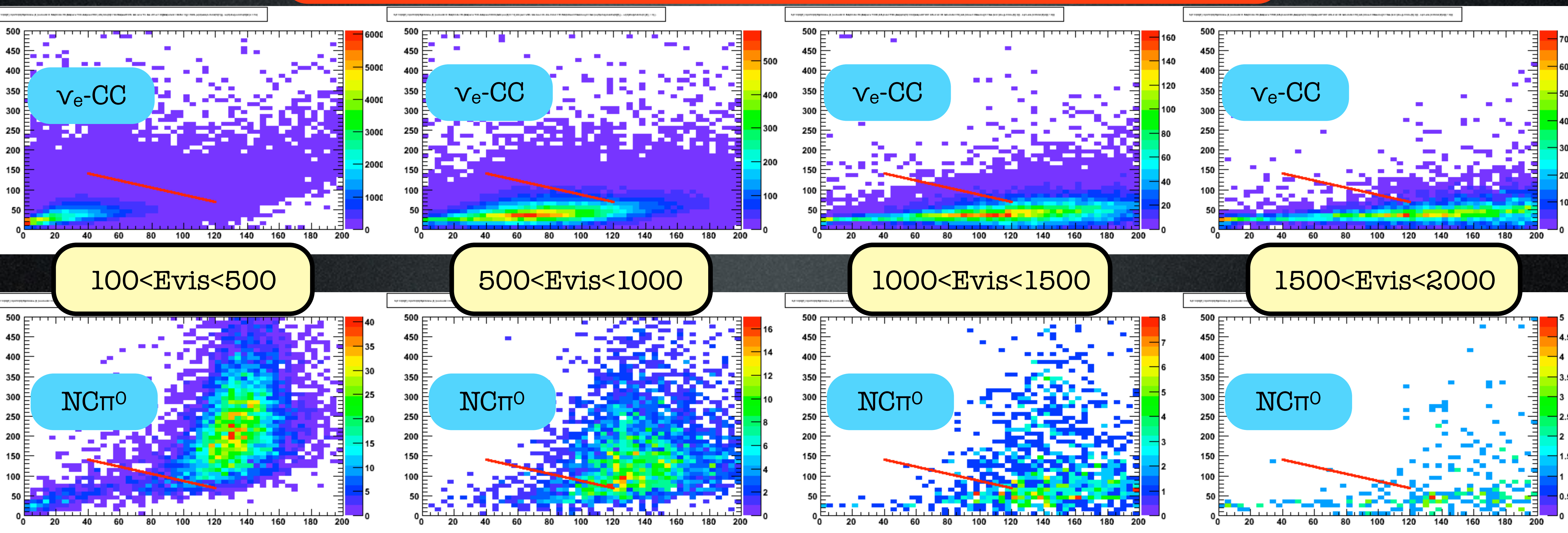




π^0 Cut at Higher Energies

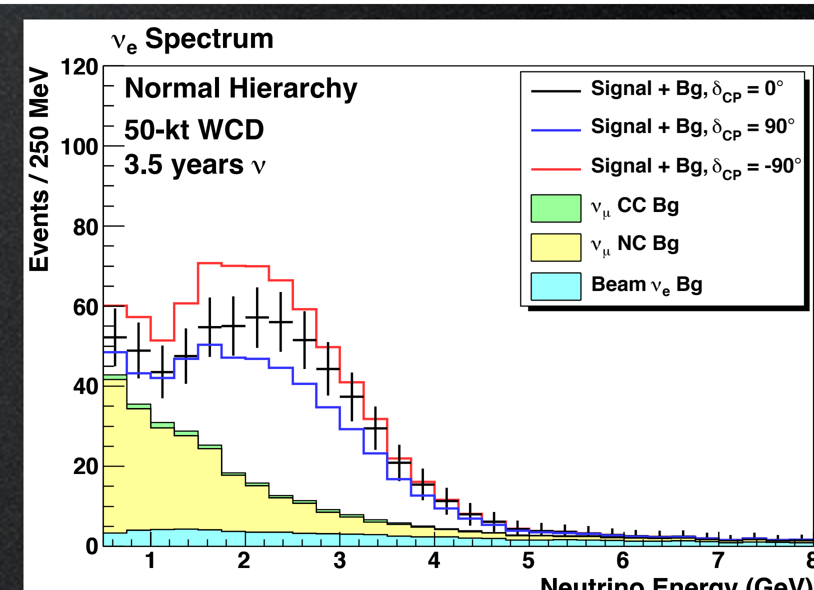
- The current π^0 cut is not optimized for high energy events

$\ln(L_{\pi^0}/L_e)$ vs M_{π^0} for the ATM MC Sample

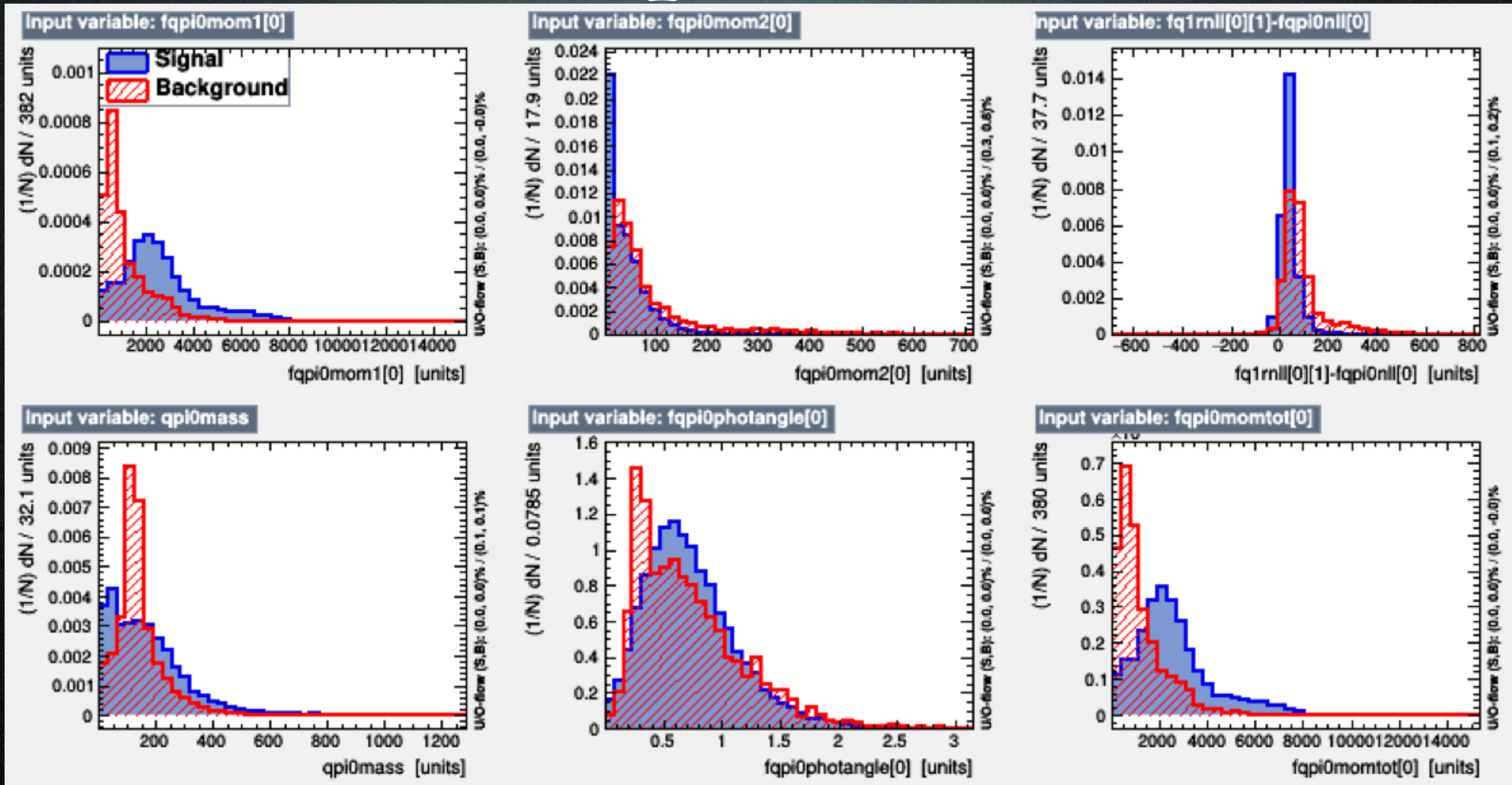


- π^0 background in LBNF beam piles up at low energy (where FiTQun π^0 cut is most effective)

- Still, need to retune the cut to be effective up to 2-3 GeV

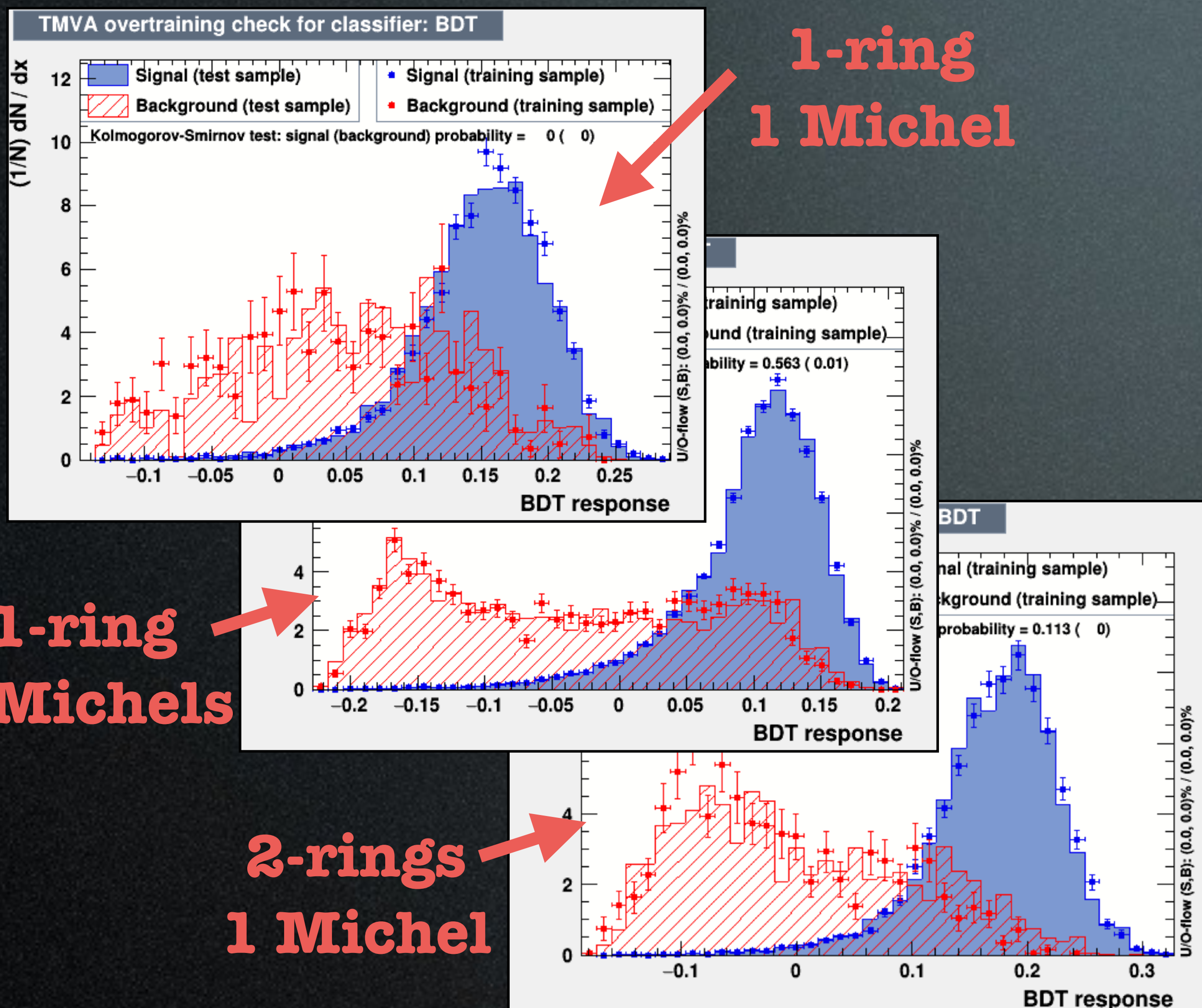


First Attempt at π^0 BDT Cut



- Relevant π^0 fit and single-e fit variables were used as inputs for a boosted decision tree

First Attempt at π^0 BDT Cut

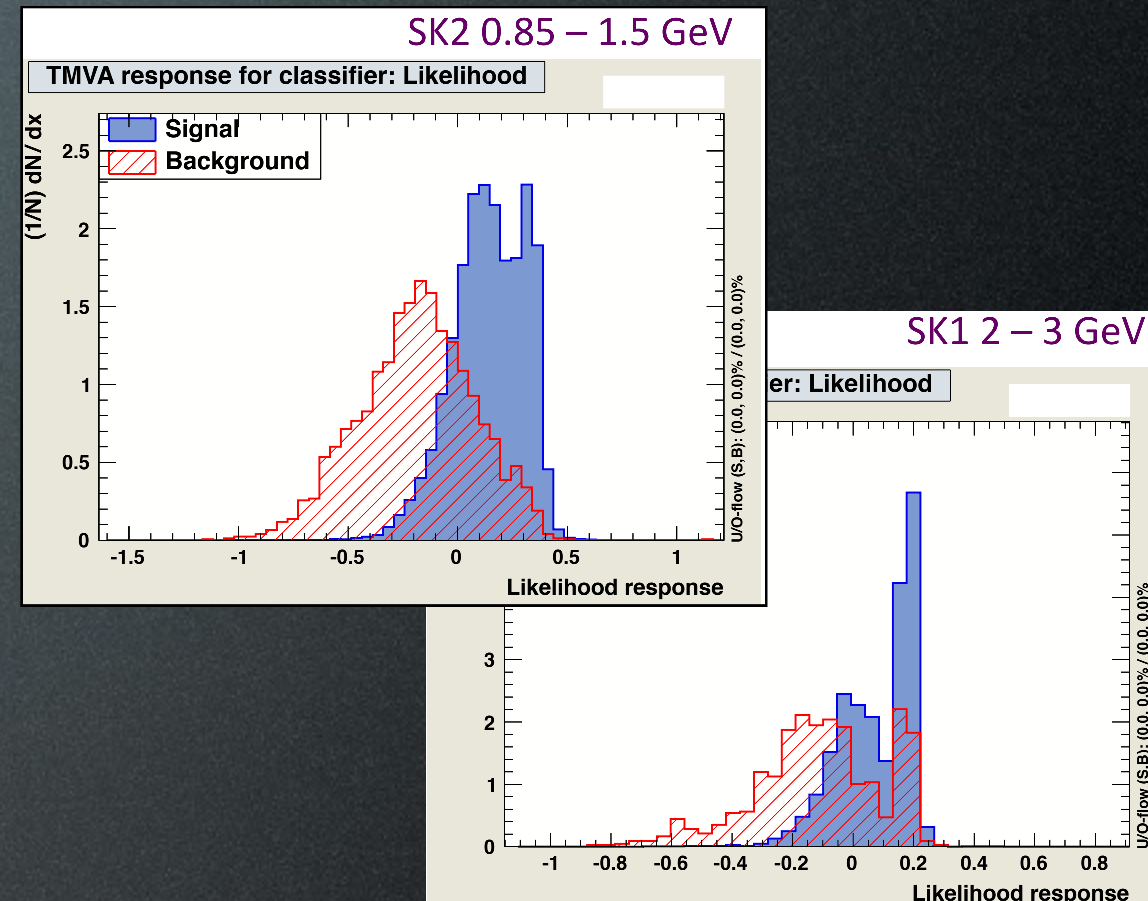


1-ring
1 Michel

1-ring
0 Michels

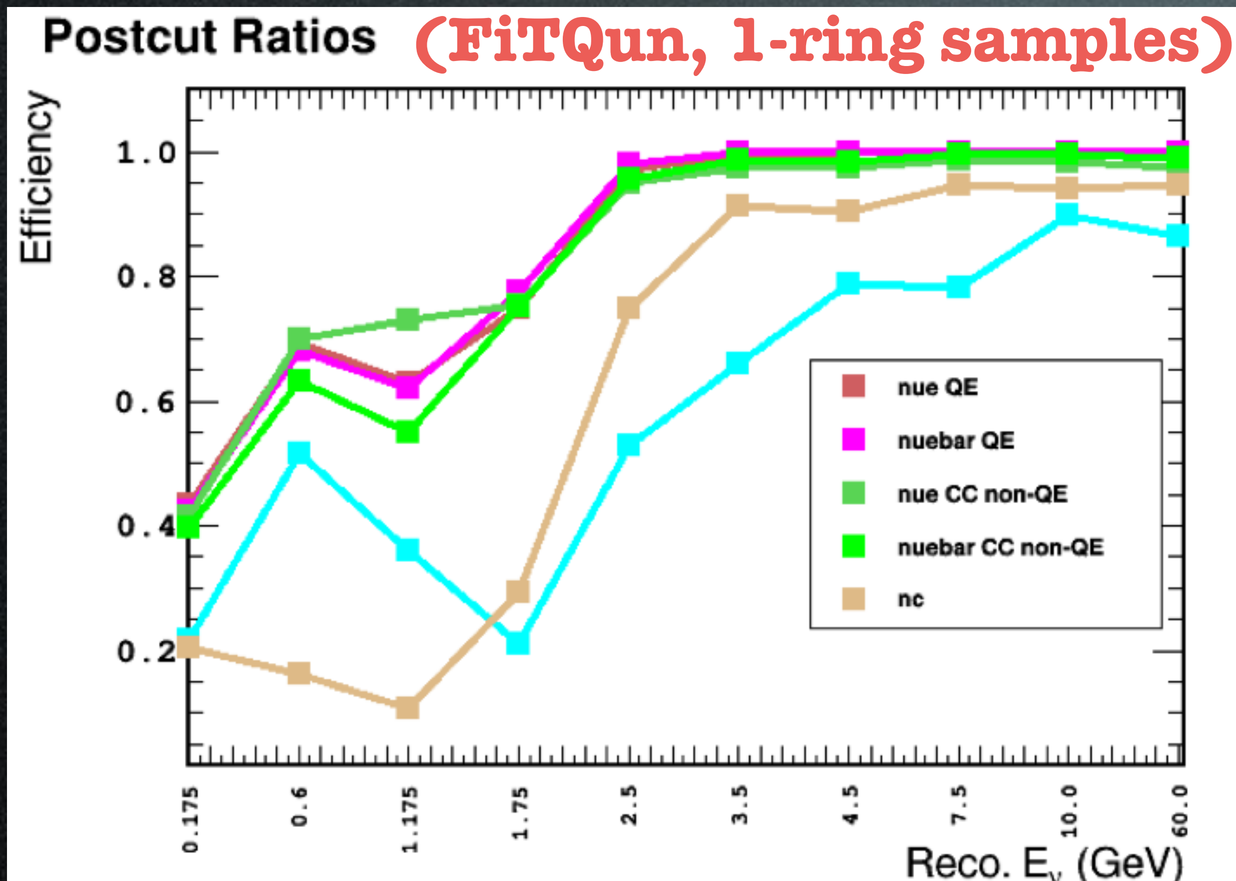
2-rings
1 Michel

LBNE Results (all 1-ring, 0 Michels)



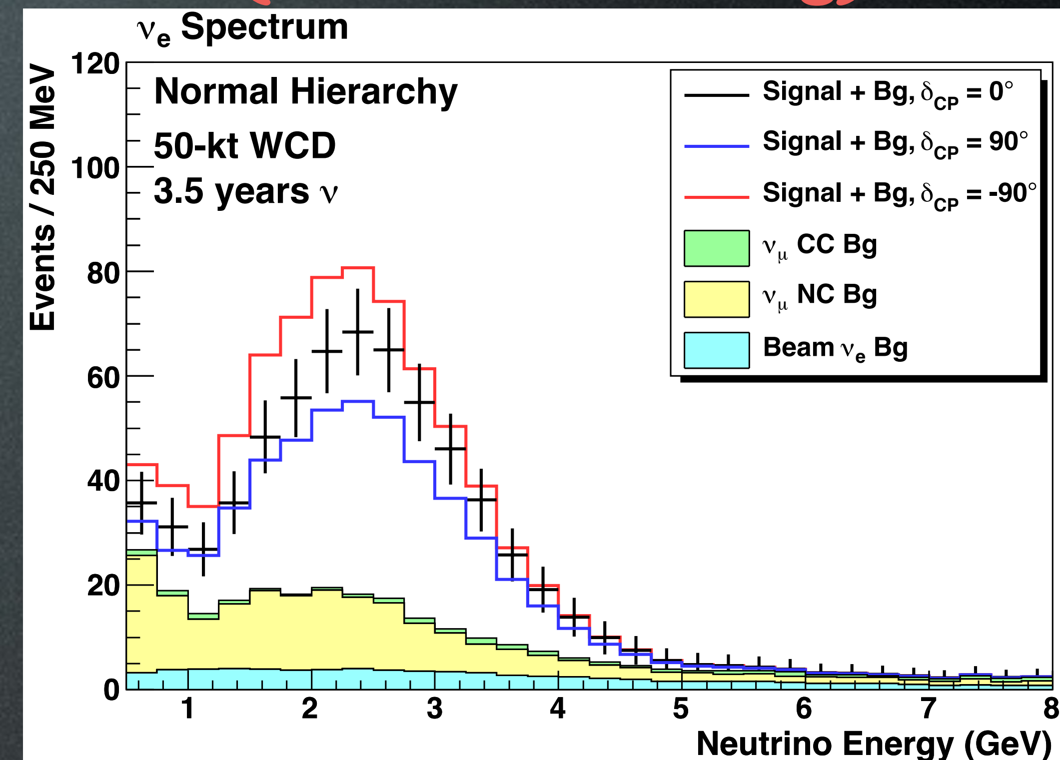
- Good NC separation seen for all 3 new samples
  - Also recall that the new selection also starts with better precut NC rejection

BDT Next Steps

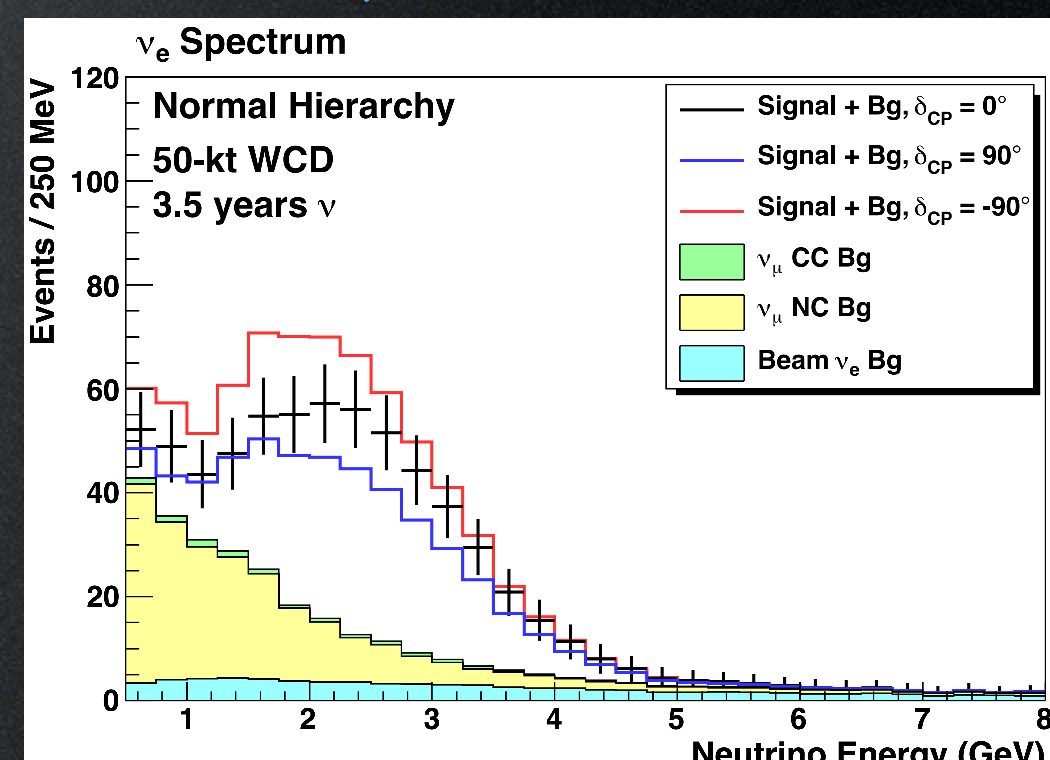


- Current cut removes "easier" π^0s at low energies without cutting much at high energy
- Need to separately train BDTs in different E_ν bins to allow us to specifically remove backgrounds in the oscillation region

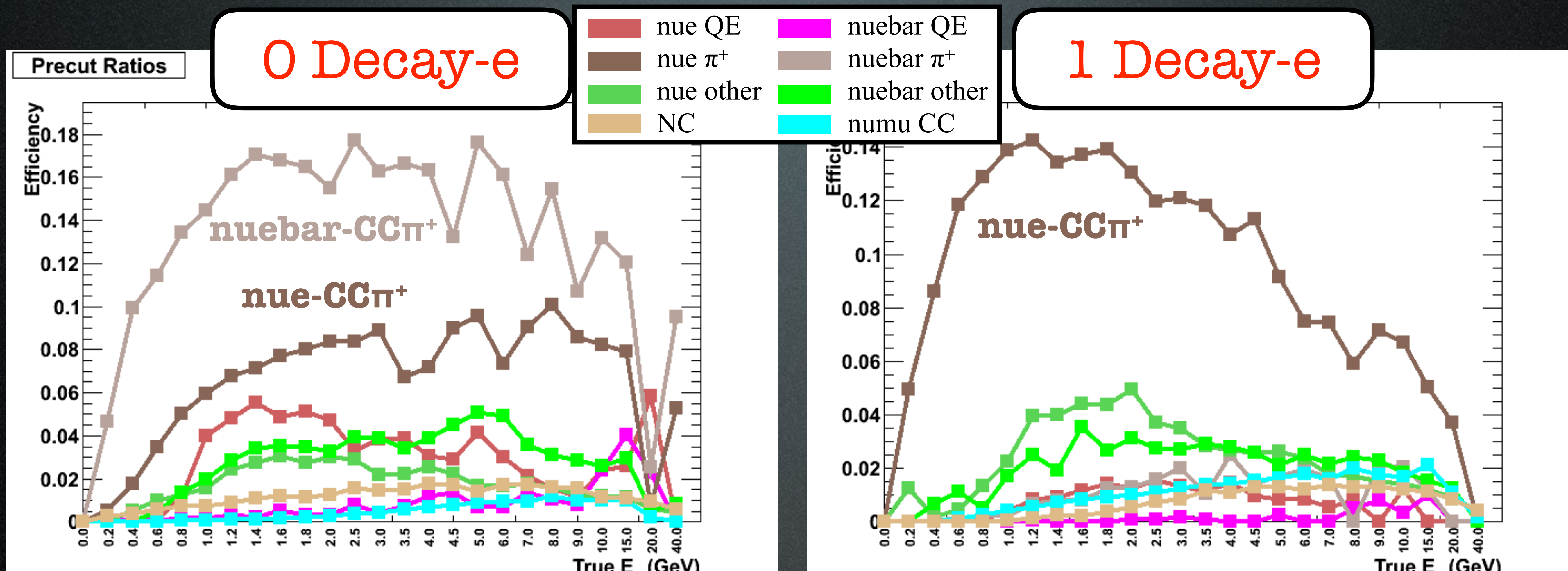
FiTQun, 1-ring samples (SK1 NC smearing)



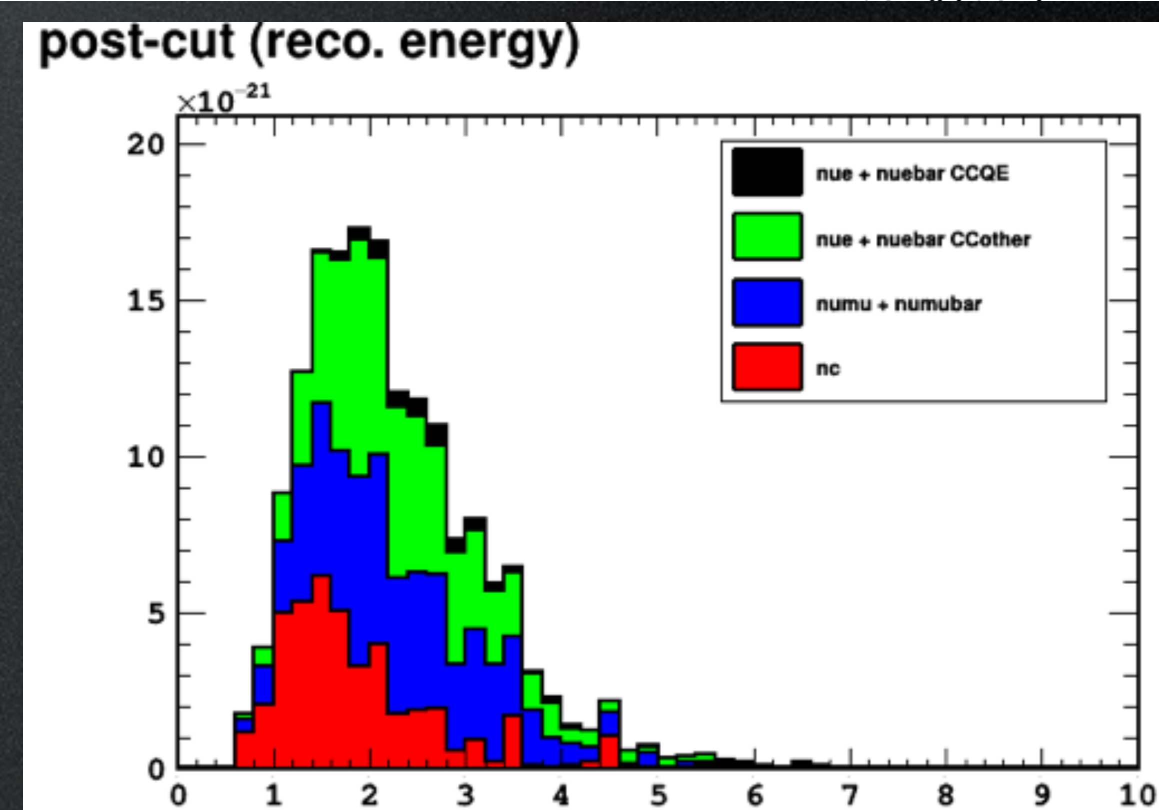
SK1, 1-ring samples



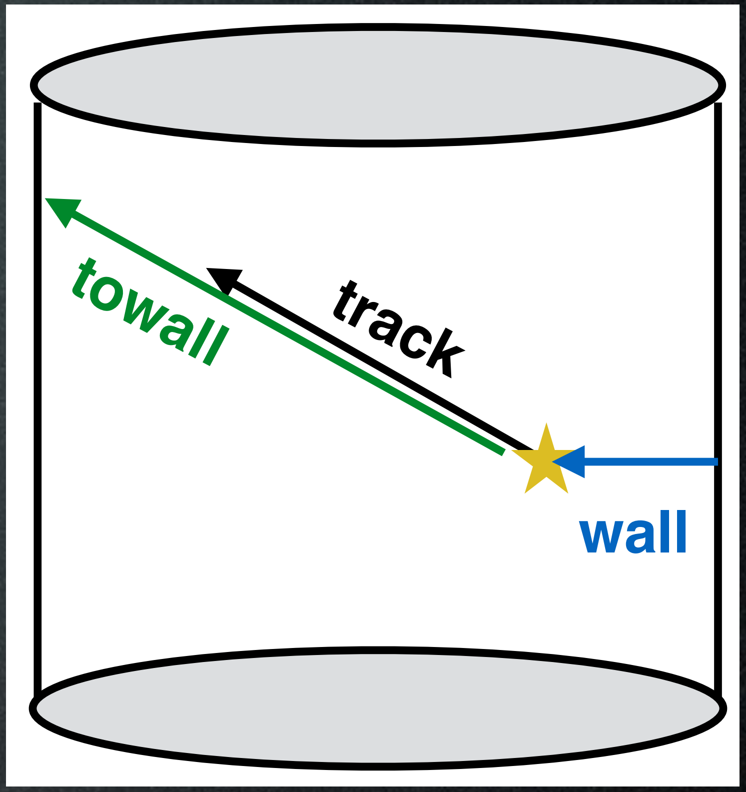
2-Ring Selection Results



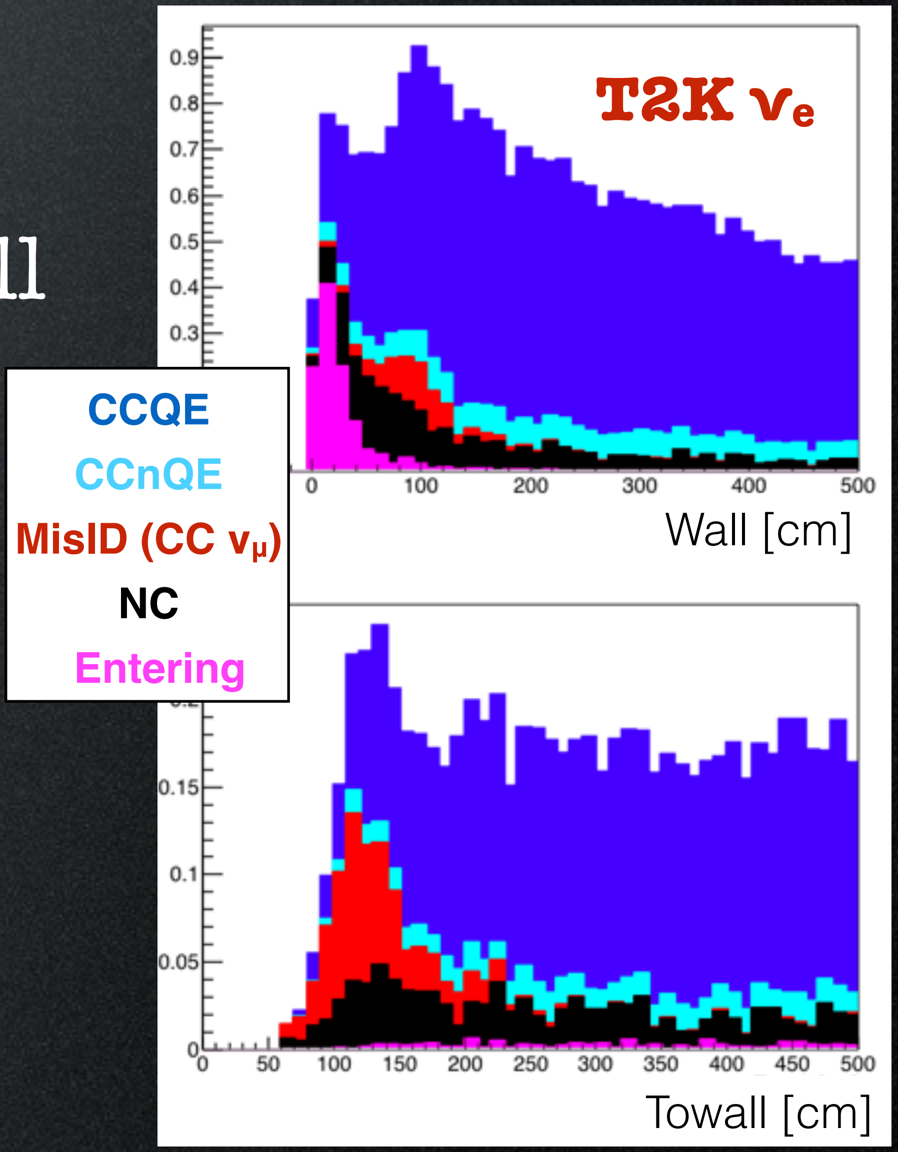
- "Efficiency" defined relative to all CCπ+ events (including below-Cherenkov π+, absorption or charge exchange in the nucleus or water, etc.)
- 2-ring, 1 decay-e (i.e. "Natural") selection for ν_e-CCπ+ shows >10% efficiency throughout the oscillation region
- ν_μ background is currently higher than is desirable; some additional event selection work is required



Increased Fiducial Volume



- Previously in Super-K, event vertices required “wall” > 2 m
- Starting this summer, T2K events will be selected 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%



Improvement Roadmap

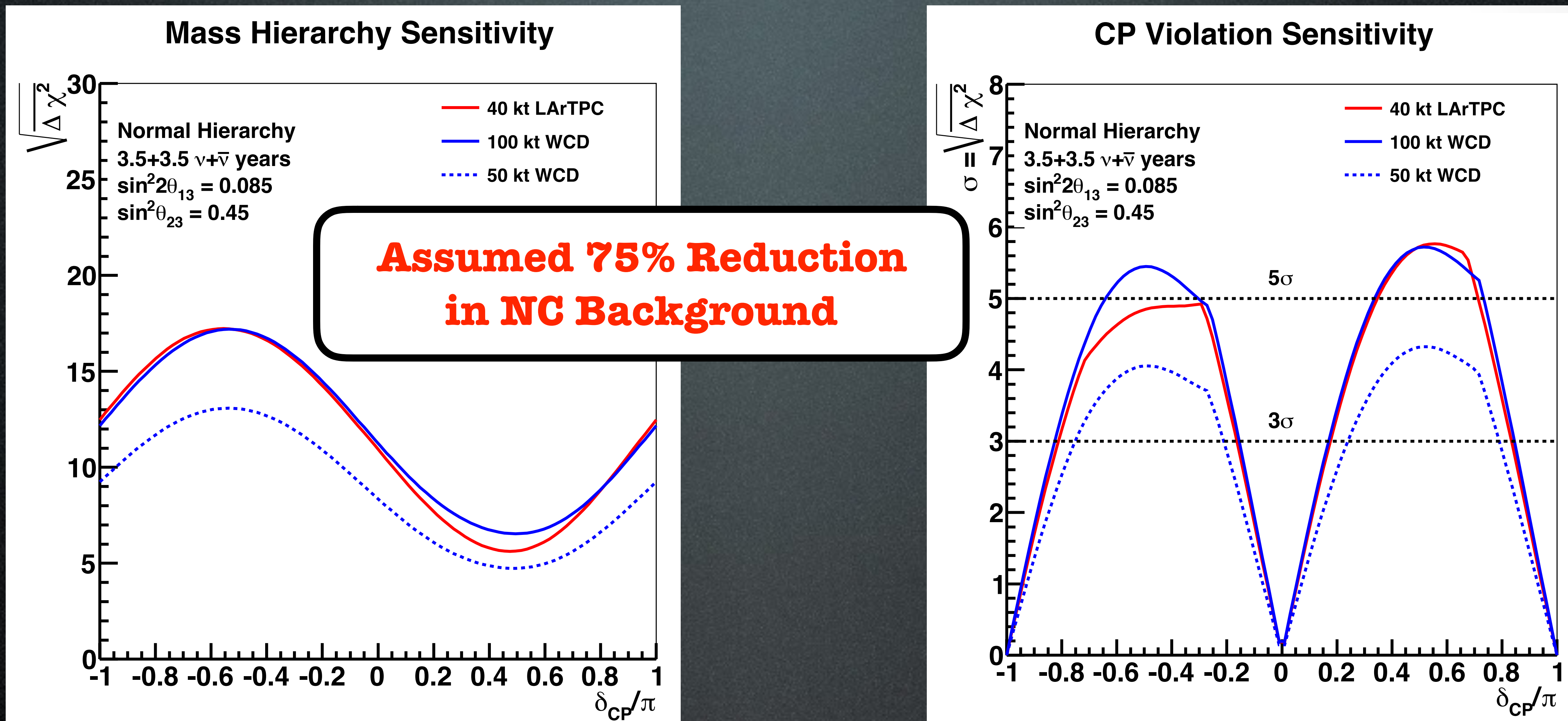
- Near term:
  - Retrain BDT cut as a function of neutrino energy to remove higher-energy π^0 background events
  - A first selection of **"1-ring" ν_e-CCπ^+** events is now included in the analysis
    - ~25% increase in ν_e statistics with slightly better purity
  - Also plan to expand the **fiducial volume** (as has been done recently at Super-Kamiokande)
    - At SK, achieve ~25% increase in 1-ring ν_e statistics with similar purity
- Medium term:
  - First pass **multi-ring ν_e-CCπ^+** event selection is now available
    - Some additional work needed to reduce ν_μ background
- Longer term:
  - Reduction of **neutral current** and **non-QE** backgrounds in the **ν_μ** disappearance sample

Summary and Next Steps

- Very close to a new, complete δ_{CP} sensitivity analysis with the improved event selection
  - Person-power ramp up over the past few months
    - ~25% of an SBU postdoc - Guang Yang, dedicated SBU undergraduate, good collaboration with Elizabeth Worcester to produce GLoBES sensitivities
  - Hope to finish first sensitivity improvement over the next few weeks
- Also plan to continue to push medium term goals (multi-ring samples) and longer term goals (FiTQun-based Cher+scint reconstruction of WbLS)

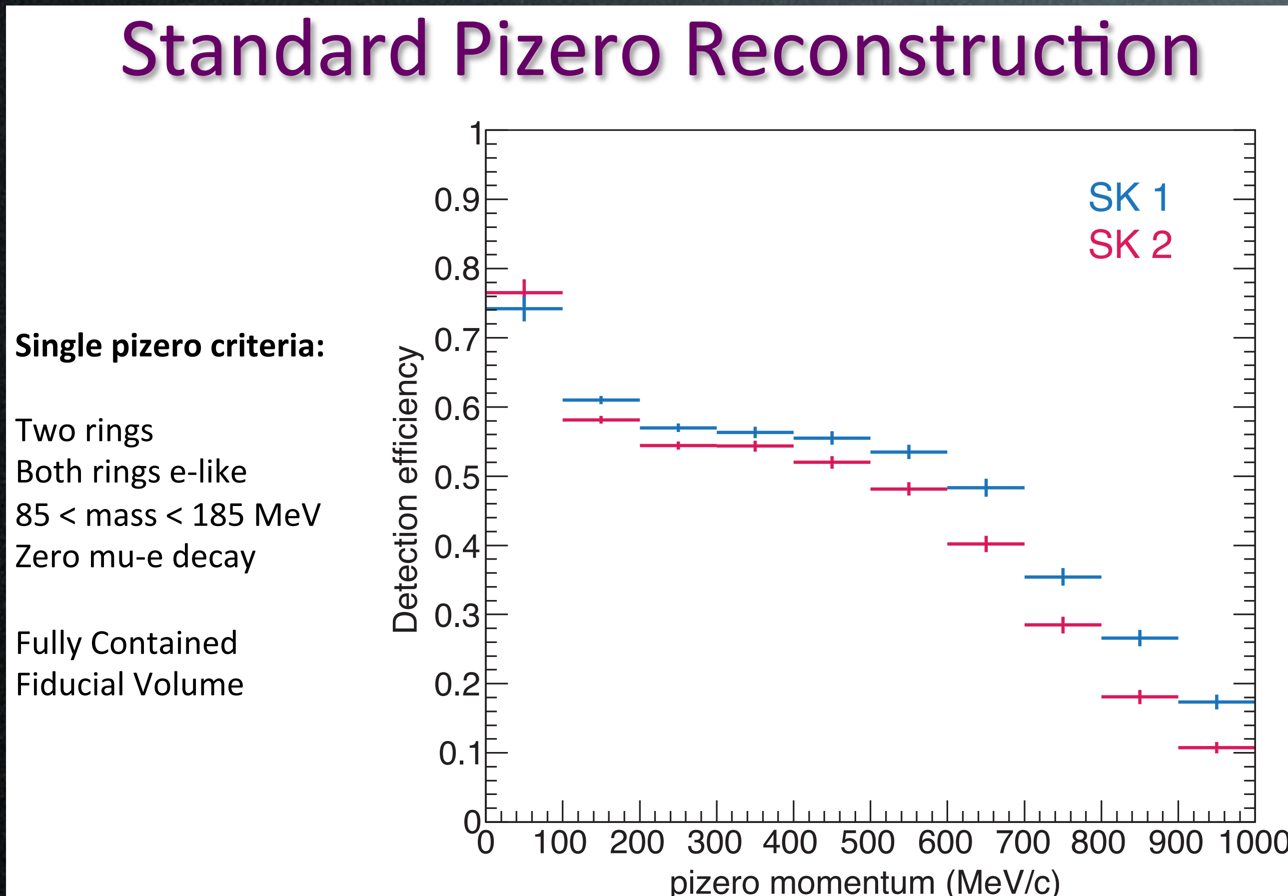
Supplement

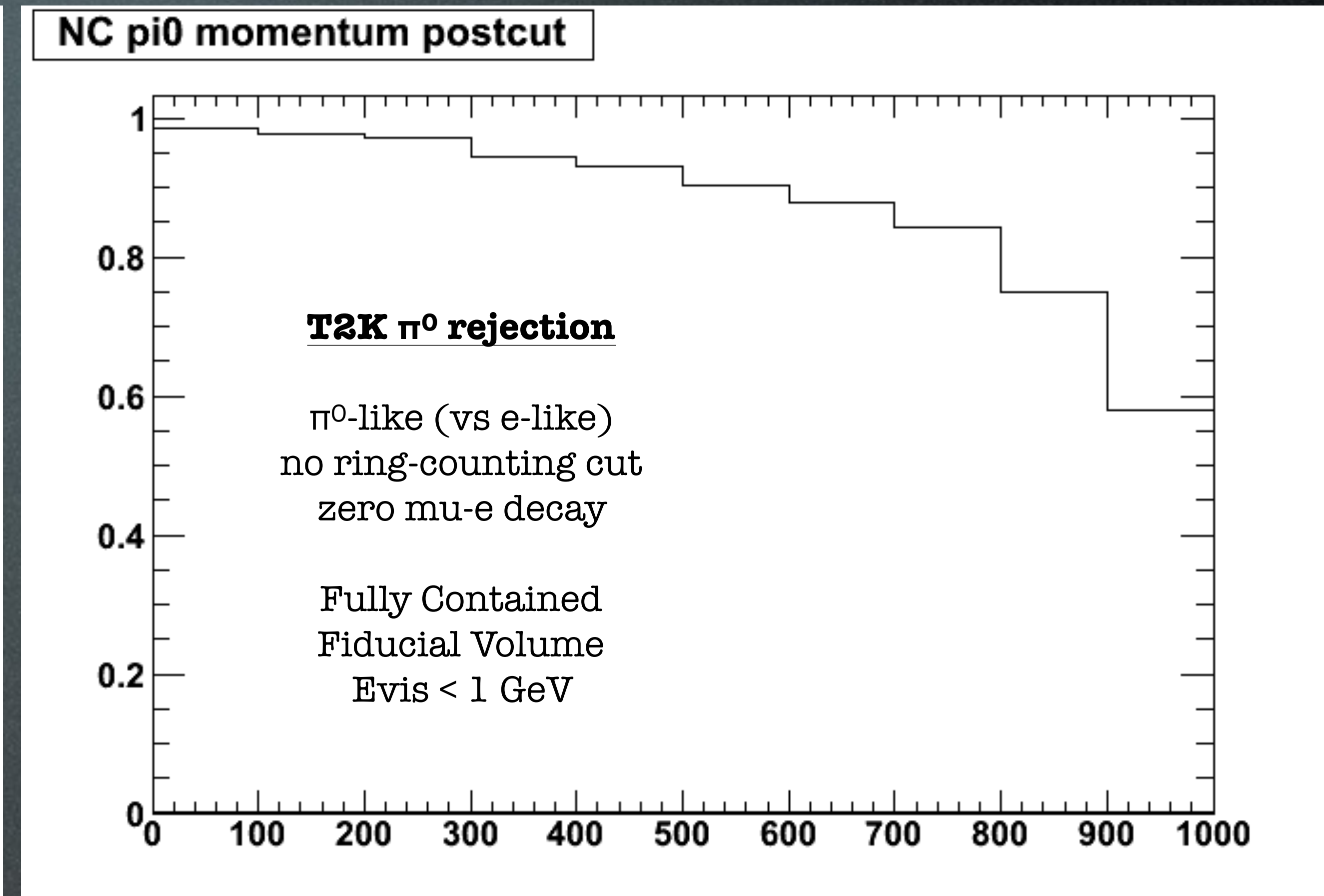
Reminder: NC Impact on Sensitivity



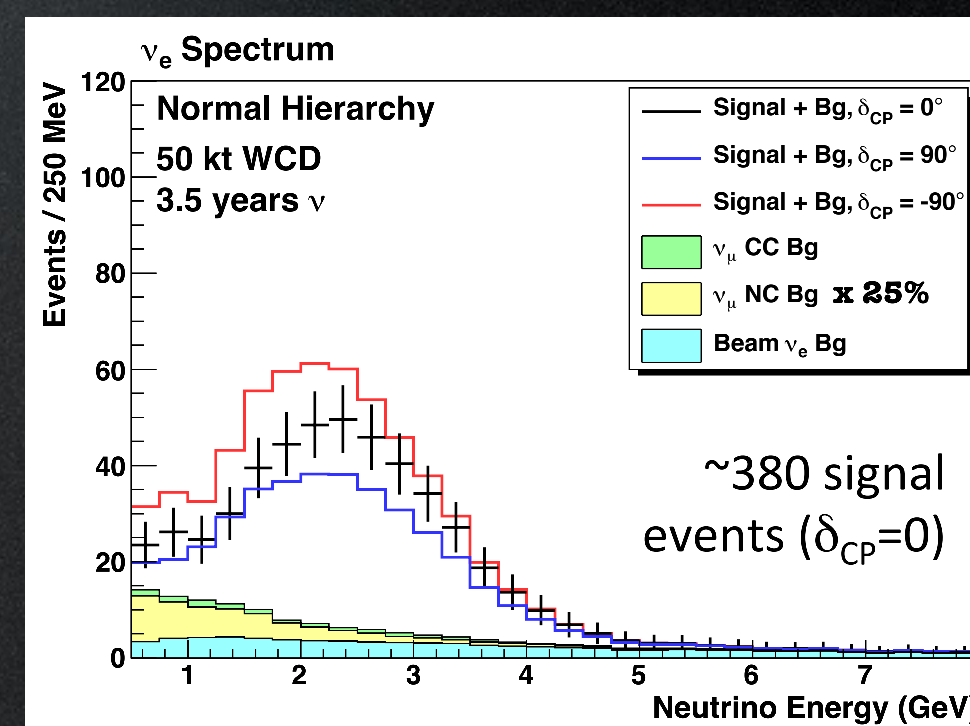
- T2K has achieved a ~70% reduction in NCπ_0 events relative to initial projections using FiTQun
- Updated LBNE sensitivities were presented at the first FroST meeting by E. Worcester
  - 40 kt of LAr produces the same sensitivity as 100 kt of water (if 75% NCπ_0 reduction)
- However, π_0 reduction at **higher E_ν** is **unexplored** ($E_{\nu,T2K}$≈0.7 GeV & $E_{\nu,DUNE}$≈2.5 GeV) and is **more difficult** (increased boost = softer 2nd photon ring)

Updated π^0 Rejection

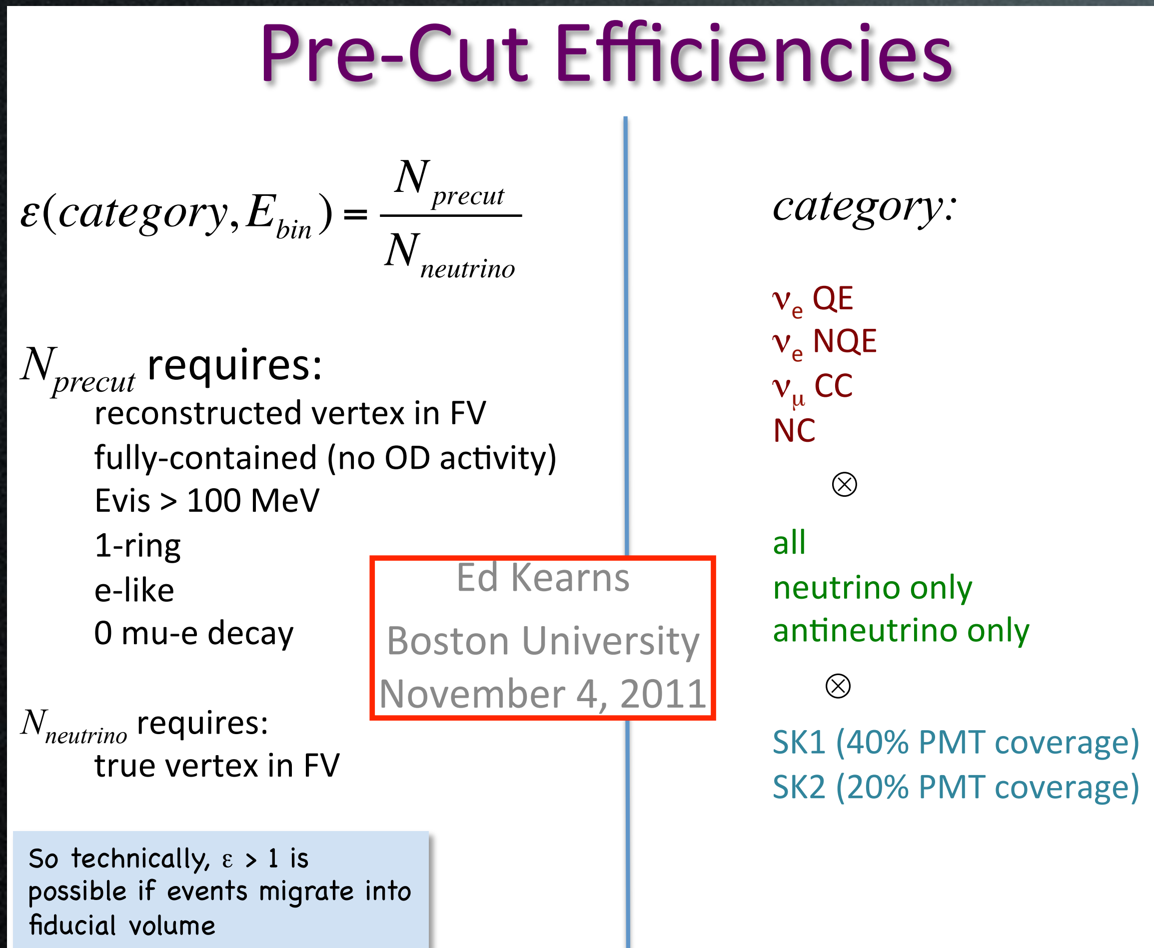


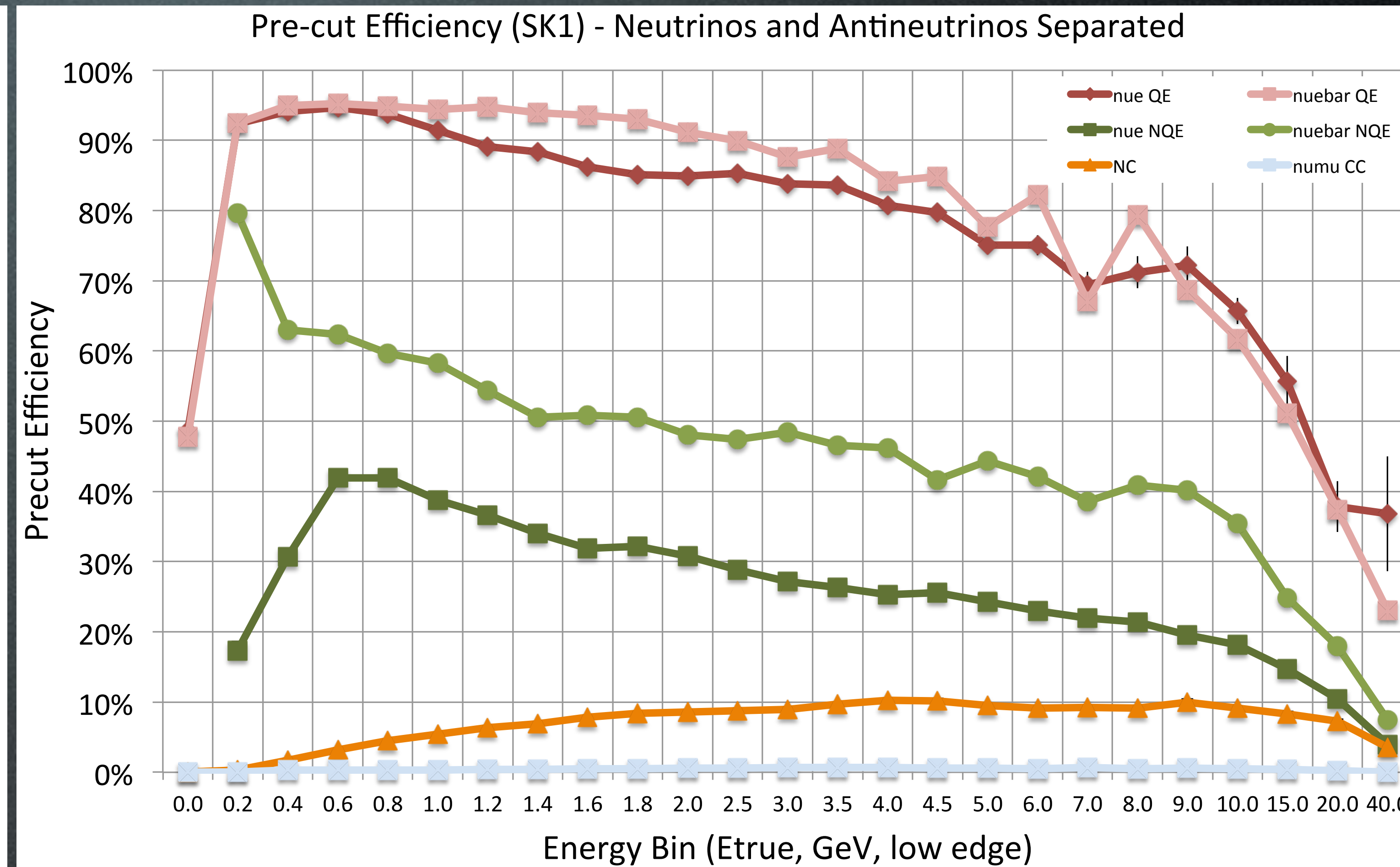


- Below $p_{\pi 0}$ of 1 GeV/c, FiTQun is much better than previous algorithms
  - Most of the DUNE NCπ^0 background has a reconstructed E_ν < 1250 MeV (current T2K cutoff)
  - Large improvement for 2nd oscillation maximum
- How much better can FiTQun do at 2 GeV?
  - Original LBNE optimization used a multi-variate analysis
- More study needed



LBNE ν_e Efficiencies



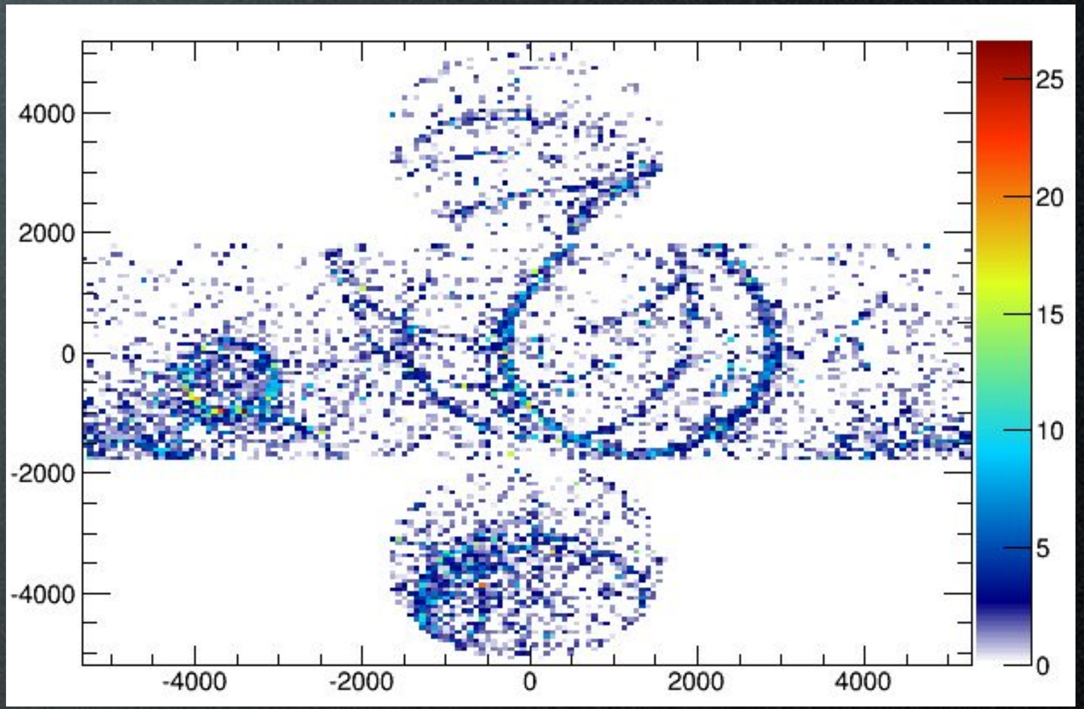


- LBNE studies based on SK1/SK2 MC
- Standard ν_e “pre-cut” selection applied
  - **1-ring**, e-like, with **ZERO** decay electrons
- “Post-cut” is an additional cut designed to remove pi0 events

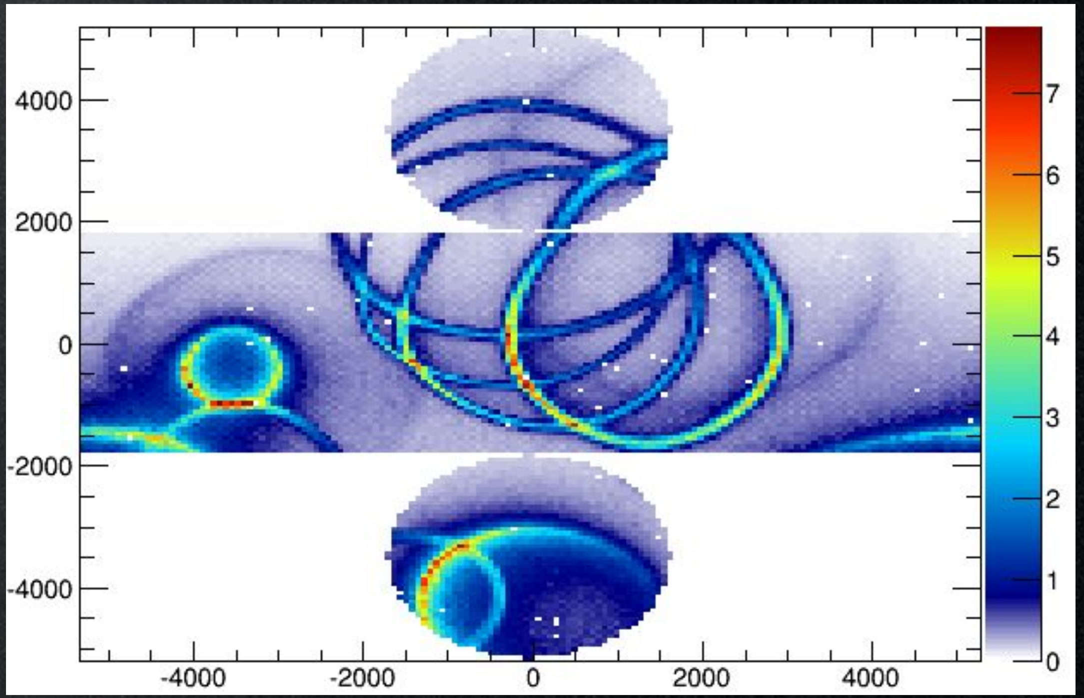
Multi-Ring Events

- If multi-ring $CC\pi^+$ and $CC\pi^0$ events can be selected, large gains in the sensitivity are possible
  - Largest cross section at the oscillation maximum
  - Existing analysis has <20% efficiency at oscillation maximum
- Studies of multi-ring $CC\pi^+$ selections are underway in T2K and Hyper-K
  - Hope to use lessons learned to produce first estimates for THEIA

Hit Charge Distribution

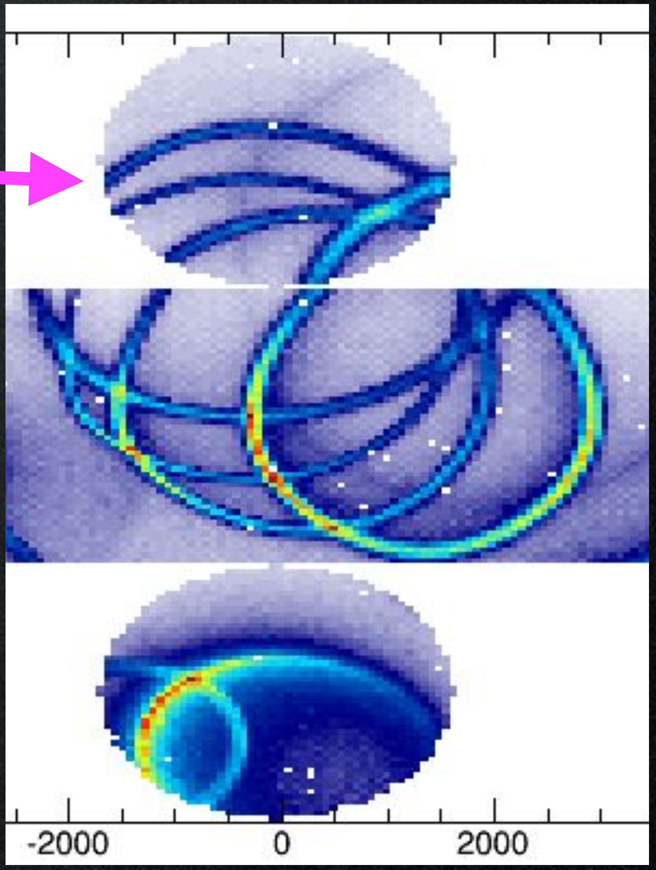


Reconstructed Predicted Charge

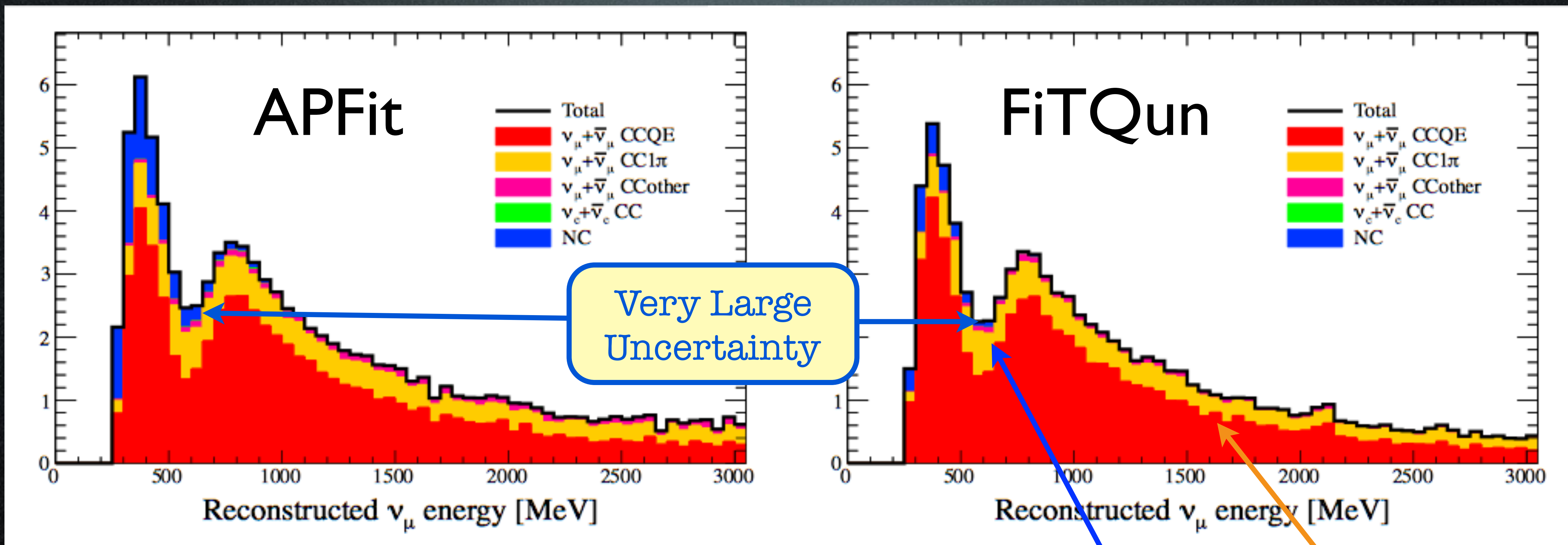


THEIA Multi-ring Selection (First Look)

- Multi-ring fitter counts electron, muon, and pion rings
- Above-Cherenkov Pions often interact hadronically
    - Produces “thin” rings
    - Multi-ring fitter can find more than 1 ring belonging to the same pion (i.e. 2 or 3 ring events)
- First out-of-the-box look at multi-ring CCπ^+ selection
    - For now, require 2-ring e + π^+ is the best fit hypothesis, where the electron is the most energetic ring
        - Quite restrictive / conservative
        - More efficiency should be recoverable with a more careful analysis



ν_μ Selection: π_+ Background Reduction



Fraction of apfit selected events removed:

$\nu_\mu+\bar{\nu}_\mu$ **CCQE**	**4.8%**
$\nu_\mu+\bar{\nu}_\mu$ **CC1π**	**21.5%**
$\nu_\mu+\bar{\nu}_\mu$ **CCoth.**	**53.7%**
$\nu_e+\bar{\nu}_e$ **CC**	**92.1%**
NC	**61.2%**

- Significant reduction of NC background due to π_+ rejection
  - NCπ_+ background has a very large uncertainty (>50%) and piles up near the oscillation dip
- **Improved sensitivity to θ_{23} & Δm_{232}**
- First implementation in T2K this summer