# Intro to Past Theia Sensitivity Calculations

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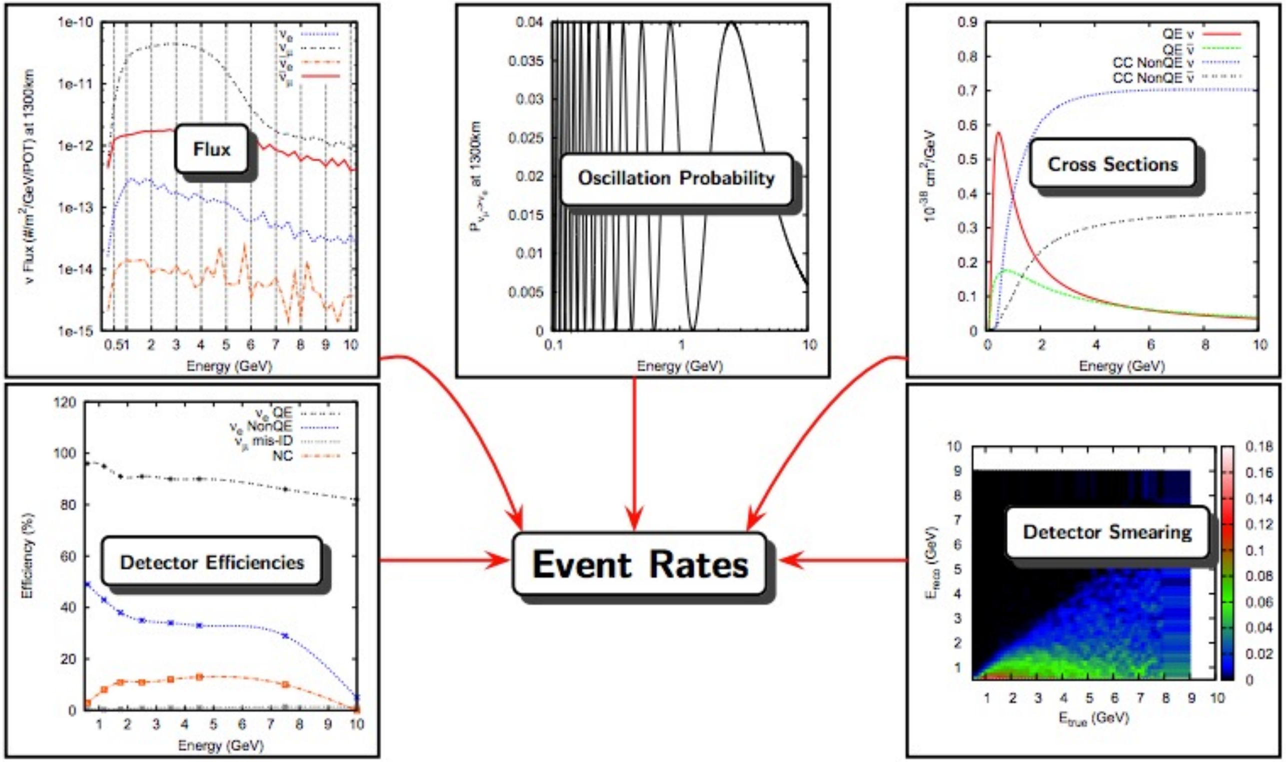
# Overview

- Current Theia LBL sensitivity calculations based on GLoBES, with approximately the same level of sophistication used in the DUNE CDR (circa 2015)
  - These studies demonstrate that a 17-kt fiducial mass Theia module **could** have similar sensitivity to a 10-kt LArTPC module in DUNE
  - Assumes SK-like WCD performance (no improvements or degradation from scintillator addition)
  - Assumes DUNE CDR normalization uncertainties (no detailed treatment of systematic uncertainties)
  - Incorporates modern SK efficiencies, including multi-ring events (Guang, Mike)
- DUNE has performed sensitivity studies using a large suite of individual sources of systematic uncertainty (flux, interaction, and detector effects) and MC samples for FD & ND for the DUNE TDR (circa 2020)
  - So far, only $\nu_\mu$ CC inclusive sample from ND-LAr included, using simple MC and parameterized reconstruction
  - Handling detector uncertainty in the ND samples is a huge difficulty with performing these sensitivity studies – fits become overconstrained very easily
  - Impact of other detectors largely demonstrated using mock data studies
- DUNE is currently updating their sensitivity analysis to include full sim/reco of ND samples, targeting an ND TDR in the coming year

# GLoBES



Flux
Oscillation Probability
Cross Sections
Detector Efficiencies
Event Rates
Detector Smearing
Energy (GeV)

# GLoBES Inputs

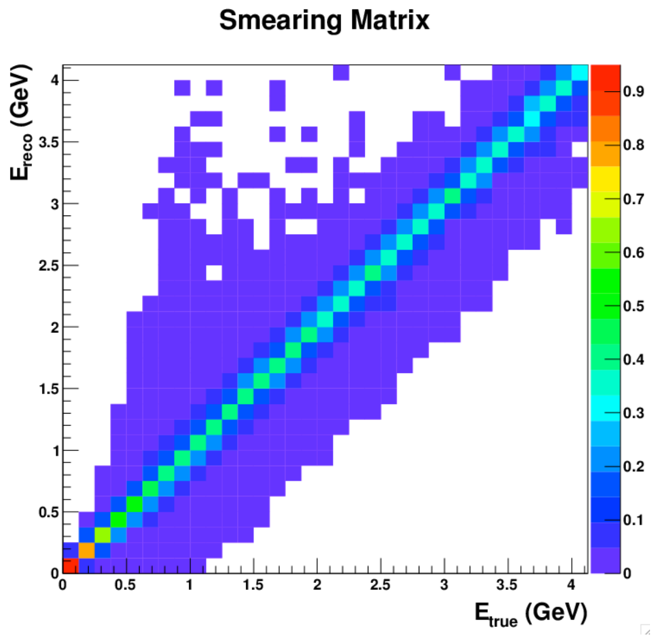
- Flux: User input
  - Our studies use public DUNE flux files
- Oscillation probability:
  - User choses central value and uncertainty in oscillation parameters
  - Can fix or float individual oscillation parameters; for the Theia fits we allow everything to vary except $\delta_{CP}$ is fixed for each point in a scan of $\delta_{CP}$ space
- Cross sections are taken from event generators
  - Our latest studies use NEUT5.3.6
- Detector smearing and efficiencies can be as simple as a Gaussian resolution with a flat efficiency (eg: 7% energy scale resolution and 80% efficiency) or as complicated as a full $E_{rec}$ vs $E_{true}$ smearing matrix with different efficiencies for each channel as a function of energy
  - Our latest studies use a full smearing matrix and channel-by-channel efficiencies as a function of energy generated with full SuperK MC
- Systematics:
  - GLoBES allows for normalization uncertainties, 100% uncorrelated among channels, such that for correlated systematics we must estimate the uncorrelated residual and apply it as a normalization uncertainty.
  - There is an option to include a simple energy scale uncertainty, but it has never been successful at capturing realistic variations – because its shape is exact it always fits out

# Theia Sensitivity Calculations

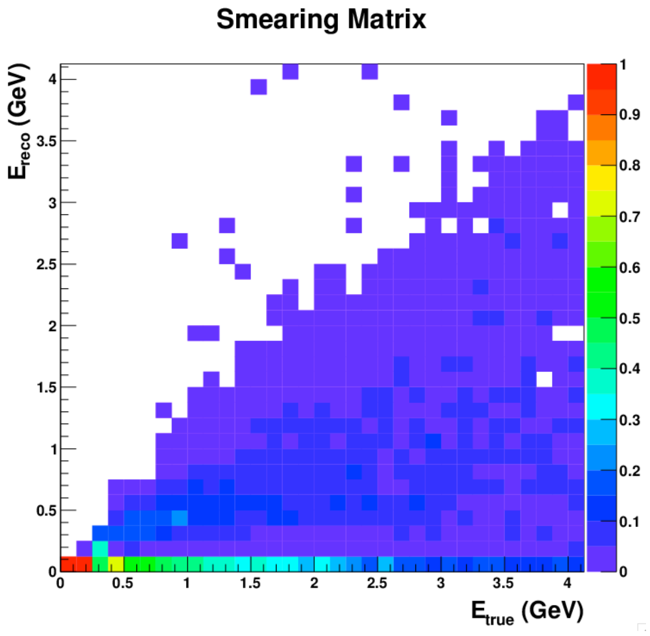
- Consider 9 appearance samples, each w/ independent systematic uncertainties
  - FHC: 1-3 rings, 0-1 decays (6 samples)
  - RHC: 1-3 rings, 0 decays (3 samples)
- Do not currently include disappearance samples
  - Minimal impact on sensitivity for the GLoBES analysis
- Pre-cut efficiencies applied as a function of true neutrino energy
- Post-cut efficiencies applied as a function of “reconstructed” neutrino energy
- Reconstructed energy calculated from smearing matrices that map $E_{true}$ to $E_{reco}$
- Fit for reconstructed energy > 0.5 GeV
- Normalization uncertainty:
  - 2% signal, 5% background, uncorrelated among all samples

# Example smearing matrixes

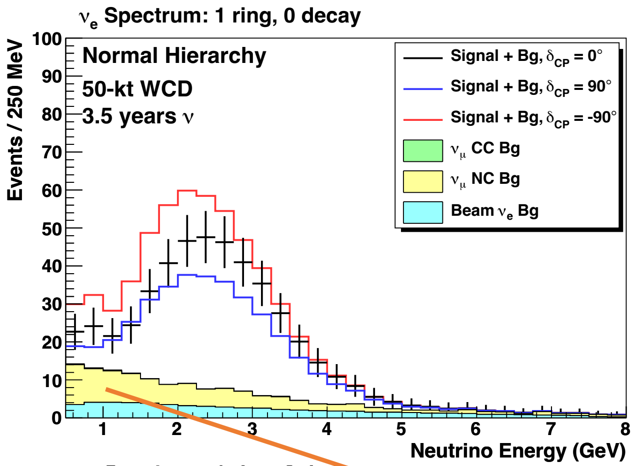
CCQE:

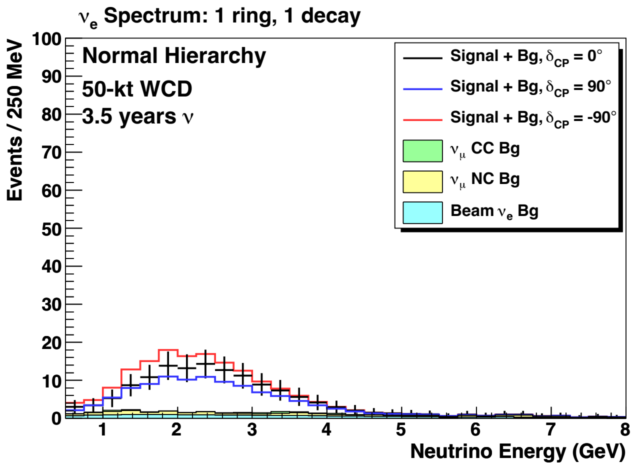


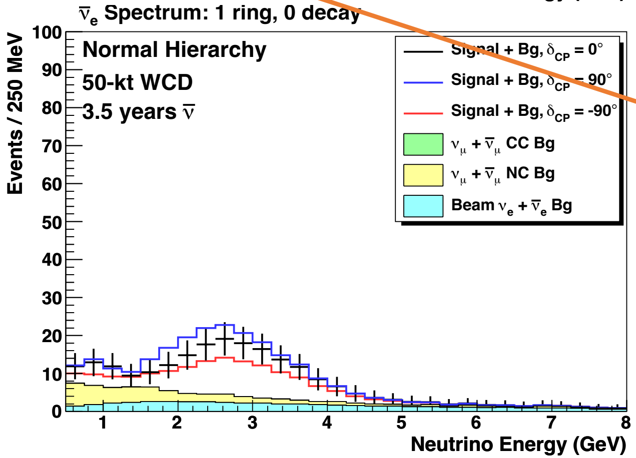

NC:



# Example Spectra




10-15 years ago, people believed that WCD would be a factor of 6 less sensitive than LArTPC in the DUNE beam (ie: would require 6x the mass for the same sensitivity), in large part because of a large NC background, which is now much more manageable using modern reconstruction, and inability to make use of multiring events

# Sensitivities (from the whitepaper)

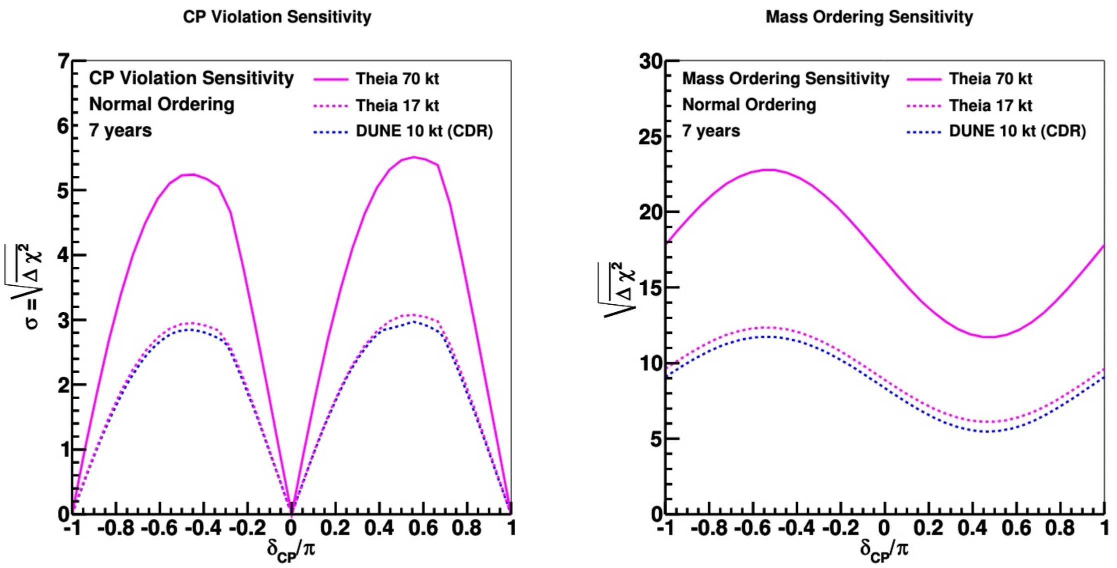



**Fig. 7** Sensitivity to CP violation (i.e.: determination that $\delta_{CP} \neq 0$ or $\pi$) (left) and sensitivity to determination of the neutrino mass ordering (right), as a function of the true value of $\delta_{CP}$, for the THEIA 70-kt fiducial volume detector (pink). Also shown are sensitivity curves for a 10-kt (fiducial) LArTPC (blue dashed) compared to a 17-kt (fiducial) THEIA-25 WCD detector (pink dashed). Seven years of exposure to the LBNF beam with equal running in neutrino and antineutrino mode is assumed. LArTPC sensitivity is based on detector performance described by [73].

Theia 17 kt similar sensitivity to DUNE 10 kt… For these simple GLoBES studies

# What is needed to make this more realistic?

- We have assumed we can achieve the same level of systematic constraint for a WCD that would be possible for the DUNE LArTPC, but the DUNE ND is designed specifically as a near detector for LArTPC
  - Differences in nuclei are not believed to be well-enough understood to extrapolate between different target nuclei - significant skepticism in DUNE collaboration that this will be possible
  - Need explicit demonstration of sensitivity using constraints from DUNE ND, which requires a simulated Theia FD sample, more sophisticated treatment of systematics with ND samples included in the fit, and a full suite of individual systematic variations (flux, xsec, detector, etc) – similar to what is planned for the DUNE ND TDR
  - We anticipate this will require more than ND-LAr samples – targeting SAND samples – and may require proposing an additional/different ND component
- We have assumed that our detector will have the same performance as HyperK – no degradation or improvement in GeV-scale performance
  - Need either full Theia simulation or studies that explicitly demonstrate this assumption is ok

# Summary

- THEIA sensitivity calculations are based on inputs from modern SuperK simulation, reconstruction, and event selection
- Theia 17 kt has similar sensitivity to DUNE 10 kt for these simple GLoBES studies (necessary but not sufficient!)
- To put our studies on a footing equivalent to current DUNE studies requires:
  - Simulation and (at a minimum) parameterized reconstruction of the Theia FD module
  - Demonstration of sensitivity using full fitting framework, including appropriate ND samples with their own realistic detector uncertainties, and a full suite of systematic variations