DUNE STRATEGY FOR CONTROLLING SYSTEMATIC UNCERTAINTY

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Outline

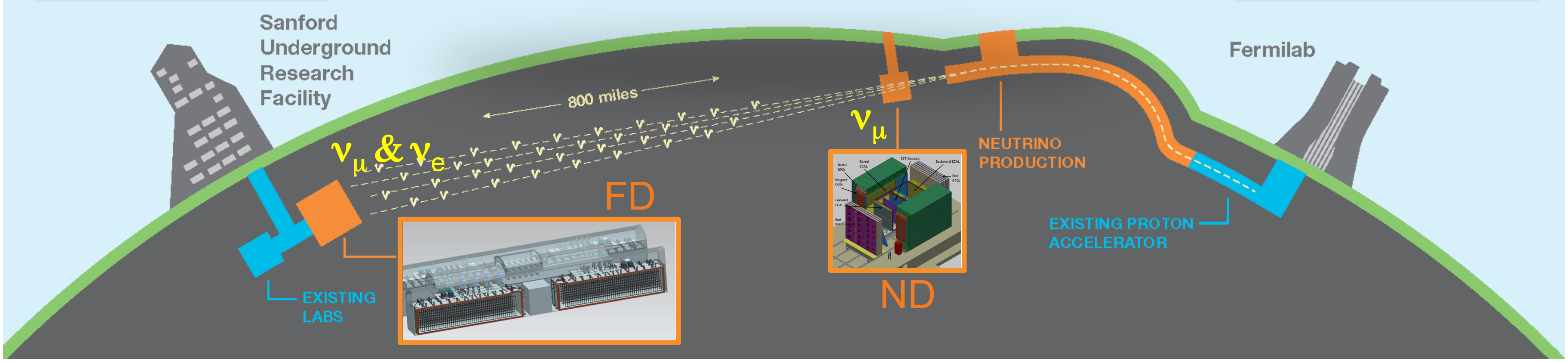
- Introduction to DUNE
  - Experiment overview
  - Tools for studying sensitivity and systematic uncertainty
- Strategy for constraining systematic uncertainty
  - Flux
  - Neutrino interaction model
  - Detector effects
- Constraining uncertainty with far detector samples
- What is needed from the NuInt community?

INTRODUCTION TO DUNE

Deep Underground Neutrino Experiment

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Measure ν_e appearance and ν_μ disappearance in a wideband neutrino beam at 1300 km to measure MH, CPV, and neutrino mixing parameters in a single experiment.

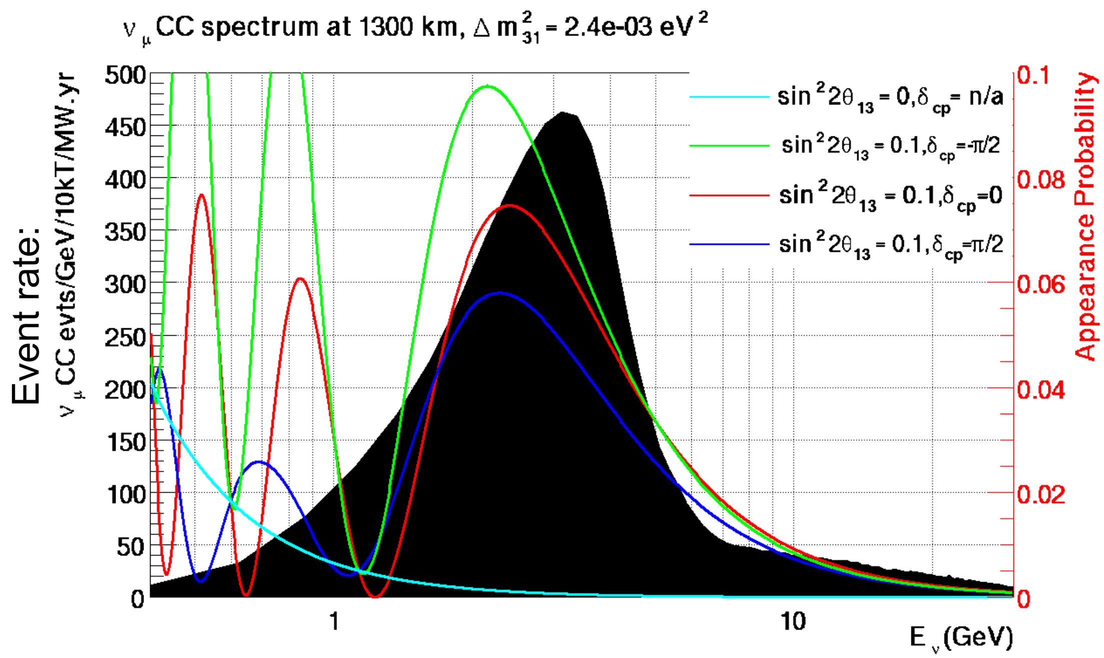


Long-baseline Oscillation

$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2 2\theta_{13}}\boxed{\sin^2\theta_{23}}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 +$$
$$\alpha\boxed{\sin 2\theta_{13}}\cos\delta\boxed{\frac{\sin(aL)}{(aL)}}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\cos\Delta_{32} -$$
$$\alpha\boxed{\sin 2\theta_{13}}\sin\delta\boxed{\frac{\sin(aL)}{(aL)}}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\sin\Delta_{32}$$

$$a = G_F N_e \sqrt{2}$$

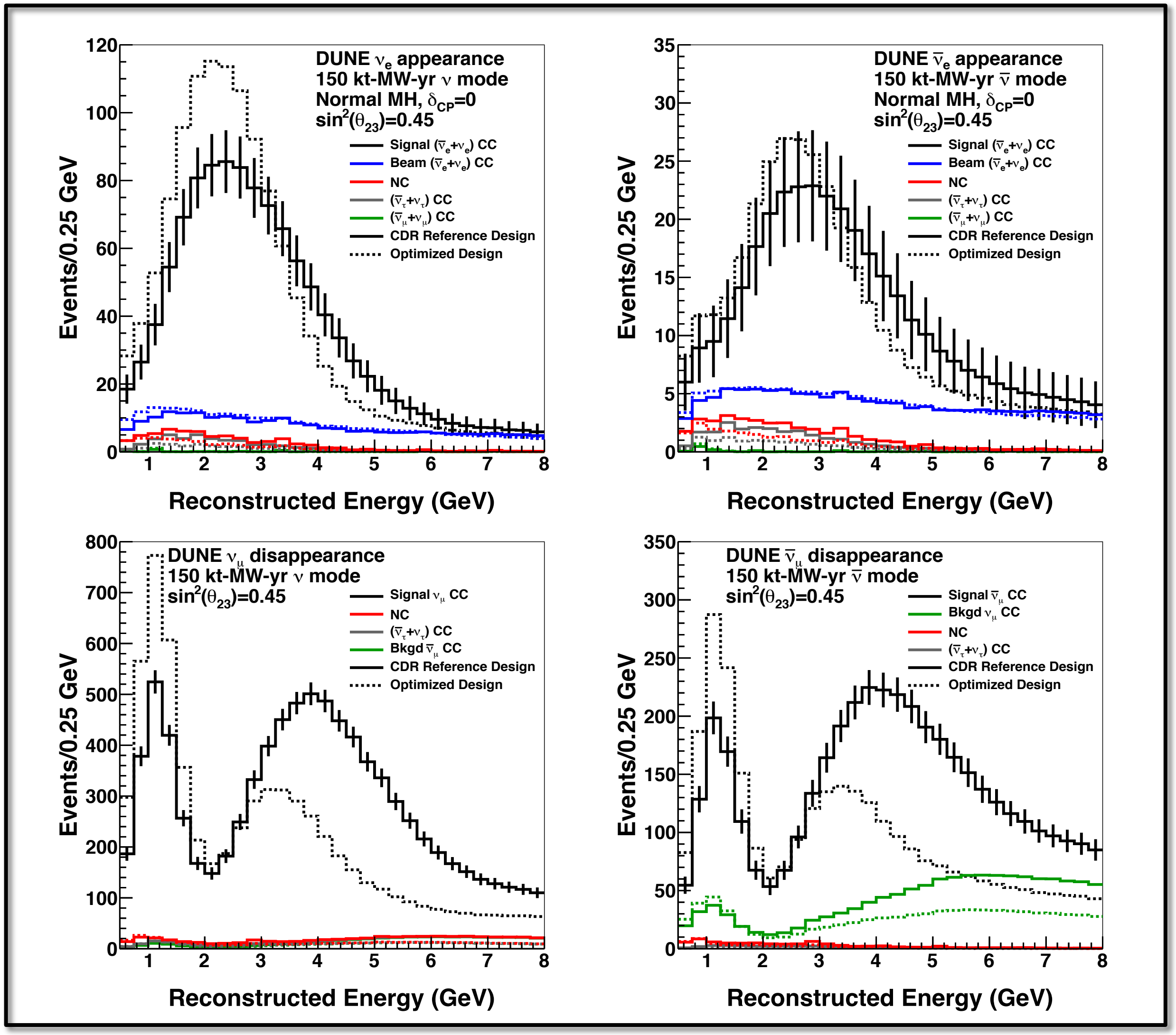
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



- ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects – measurements of all four possible in a single experiment
- Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample

Far Detector Spectra

DUNE CDR:



- 80-GeV, 1.07 MW proton beam, planned upgrade to >2 MW after 6 years
- Two horn-focused neutrino beam line designs considered
- GENIE event generator
- Signal and background reconstructed energies and efficiencies calculated using detector response parameterized at the single particle level
- O(1000) appearance events in 300 kt-MW-yrs
- >10,000 disappearance events in 300 kt-MW-yrs
- 300 kt-MW-yrs ~ 7 years

Simple Systematics Treatment

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Sensitivities in DUNE CDR are based on GLoBES calculations in which the effect of systematic uncertainty is approximated using signal and background normalization uncertainties. Spectral uncertainty not included in this treatment.
- Signal normalization uncertainties are treated as *uncorrelated* among the modes (ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$) and represent the residual uncertainty expected after constraints from the near detector and the four-sample fit are applied
  - $\nu_\mu = \bar{\nu}_\mu = 5\%$ → Flux uncertainty after ND constraint
  - $\nu_e = \bar{\nu}_e = 2\%$ → Residual uncertainty after ν_μ and $\nu/\bar{\nu}$ constraint
- Oscillation parameter central values and uncertainties are taken from NuFit 2014 (circa Neutrino 2014). Parameters are allowed to vary constrained by the uncertainty in the global fit.

Effect of Normalization Uncertainty

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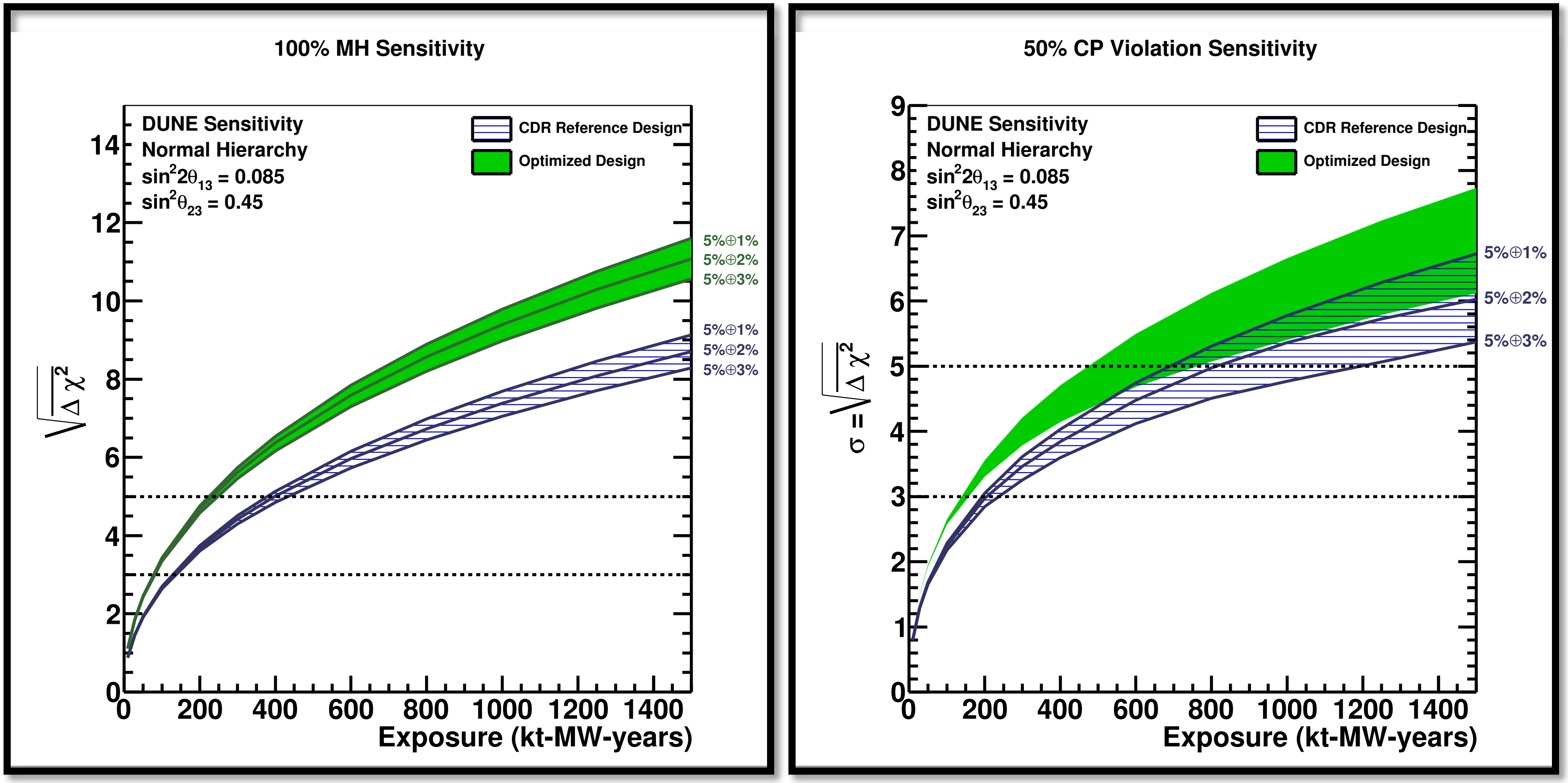
DUNE CDR:



Statistically limited for ~100 kt-MW-years. Uncertainty in ν_e appearance sample normalization must be ~5% ⊕ 2% to discover CPV in a timely manner.

DUNE Analysis Tools

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- GLoBES
  - Flux from GEANT4 beam simulation
  - GENIE cross sections
  - Energy reconstruction and signal/bg efficiency from Fast MC
  - GLoBES oscillation Fitter
- Fast MC
  - Flux from GEANT4 beam simulation
  - GENIE interaction simulation (4-vectors for each resulting particle)
  - Detector response parameterized at single particle level
  - Reconstructed quantities and selection criteria based on realistic kinematics
  - Background reduction algorithms including dE/dx separation for NC and kNN algorithms for NC and ν_τ are applied
  - MGT oscillation fitter
  - Reweighting technique to evaluate effect of systematic uncertainty
- MGT
  - GLoBES-based oscillation fitter
  - Can include effect of individual systematics and statistical fluctuations
- VALOR
  - Adapted from T2K
  - Fit near detector samples to obtain constraints on systematics parameters including flux and cross-sections
- LArSoft
  - Flux from GEANT4 beam simulation
  - GENIE interaction simulation
  - GEANT4 detector simulation
  - Parameterized propagation of ionization electrons and scintillation photons
  - Parameterized simulation of electronics response

Fast MC/MGT Details

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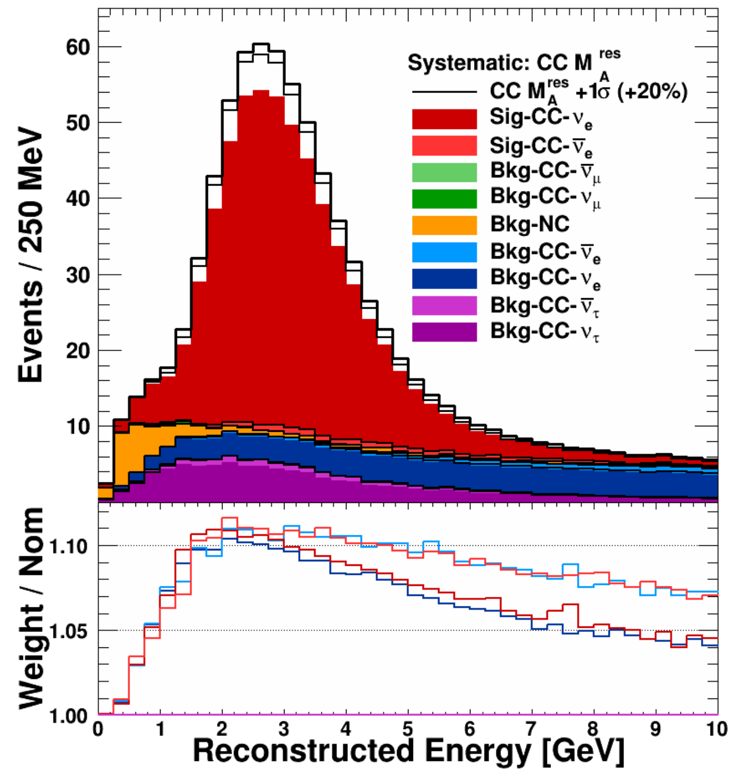
- Fast MC = Flux simulations + GENIE + parameterized detector response
- Detector response parameterization based on inputs from LArSoft simulations, GEANT4, and ICARUS
- Reconstructed quantities and selection criteria based on realistic kinematics
- MGT fitter includes statistical limitations on constraints from four-sample fit and uncertainty in sample-sample correlation

DUNE CDR: Single particle detector response. Many values quite conservative.

Particle type	Detection Threshold (KE)	Energy/Momentum Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained track: track length Exiting track: 30%	1°
$\pi^{\pm}$	100 MeV	μ-like contained track: track length π-like contained track: 5% Showering or exiting: 30%	1°
$e^{\pm}/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{E}$[GeV]	1°
p	50 MeV	p<400 MeV/c: 10% p>400 MeV/c: $5\% \oplus 30\%/\sqrt{E}$[GeV]	5°
n	50 MeV	$40\%/\sqrt{E}$[GeV]	5°
other	50 MeV	$5\% \oplus 30\%/\sqrt{E}$[GeV]	5°



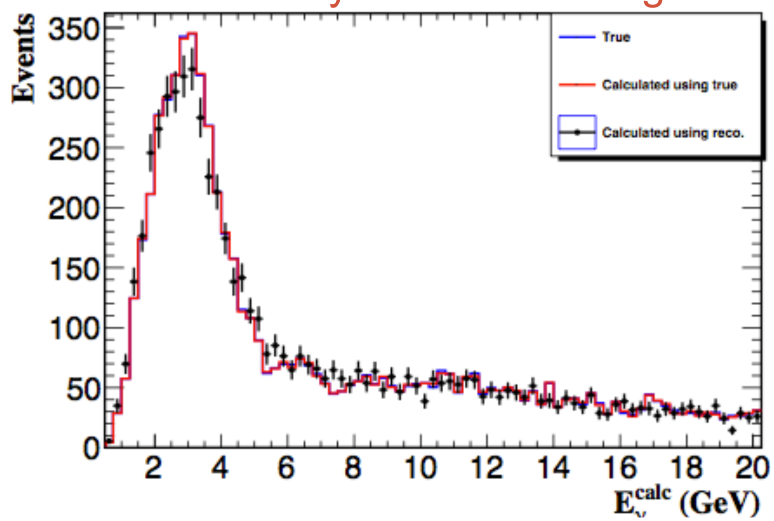
Example: ν_e appearance spectrum showing variation that is induced by changing the value of M_A^{RES} by +1σ in the simulation

STRATEGY FOR CONSTRAINING SYSTEMATIC UNCERTAINTY

Strategy for Flux

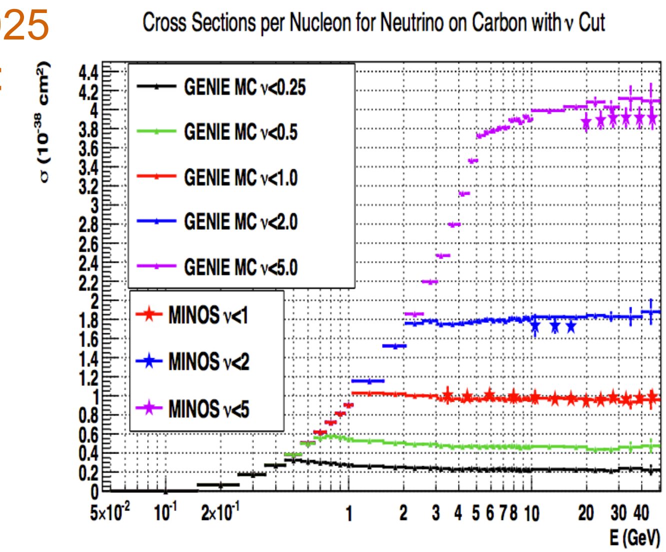
- Constrain absolute flux with near detector measurements of fully-leptonic neutrino interactions
  - Cross-sections known to high precision
  - Neutrino-electron scattering: ~3% stat. ($E_\nu < 5$ GeV)
  - Inverse muon decay: ~3% stat. ($E_\nu > 11$ GeV)
- Constrain flux shape using low-ν_0 method: 1-2%
- Low-ν_0 measurement for both ν_e and ν_μ flux, in combination with hadron production data (NA61/SHINE), constrains ND/FD flux ratio at the 1% level

Fast MC study of ν-e scattering:



120 events in MINERvA → 13% constraint on NuMI flux, statistically limited (J. Park thesis)

arXiv:1201.3025 (Bodek et al.):



Strategy for Interaction Model

- Prospects for improved interaction models:
  - Improved models becoming available
  - Intermediate neutrino program measurements in LAr TPCs
- ND constraint:
  - High precision near detector designed to constrain cross-section and hadronization uncertainties, resolving many individual particles produced by resonance and DIS interactions
  - Argon nuclear targets in ND allows significant cancellation of cross-section uncertainties common to near and far detectors
- FD constraint:
  - Four FD samples allow cancellation of uncertainties that are correlated between ν_e/ν_μ or $\nu/\bar{\nu}$

Improving Interaction Models

- Worldwide effort that will benefit DUNE!
- Alternative models being implemented in GENIE include:
  - Long- and short-range correlations among nucleons
  - Effect of random phase approximations
  - Meson exchange currents
  - 2p-2h effects in CCQE
  - Effective spectral functions
  - Coherent pion production
  - Alternative model of DIS interactions
  - Variation of tunable parameters within existing models
- Comparisons among generators
- Neutrino interaction data available or coming soon from:
  - ArgoNeuT, MINERvA, CAPTAIN-MINERvA, NOvA-ND, T2K-ND280, μBooNE, SBND, ICARUS, …
- Electron-argon scattering data coming soon from JLab

DUNE collaborators active in all of these efforts!

Strategy for Detector Effects

- DUNE LArTPC expected to perform better than existing appearance experiments in reconstruction of ν_e interactions
  - Purity of quasielastic-like sample improved by detection of low-energy hadronic showers
  - Low threshold and good resolution improves calorimetric reconstruction
  - Experience from Intermediate Neutrino Program LArTPCs expected to inform simulation, reconstruction, and calibration of DUNE's far detector
- Calibration program
  - LArIAT, CAPTAIN, DUNE 35-ton prototype, protoDUNE
- Improved neutrino interaction model will reduce impact of imperfect reconstruction of neutrons and low-energy protons on analysis

DUNE 35-ton APAs:

Strategy for Detector Effects

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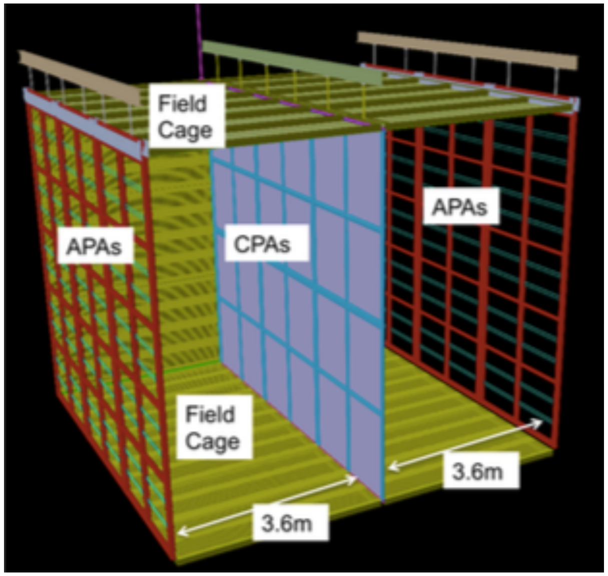
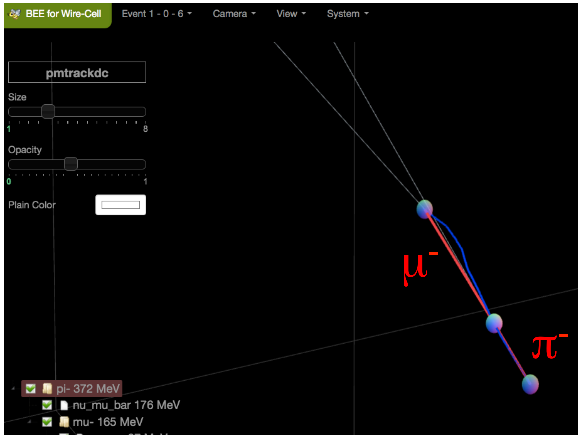
protoDUNE:



protoDUNE MC:
500 MeV pion

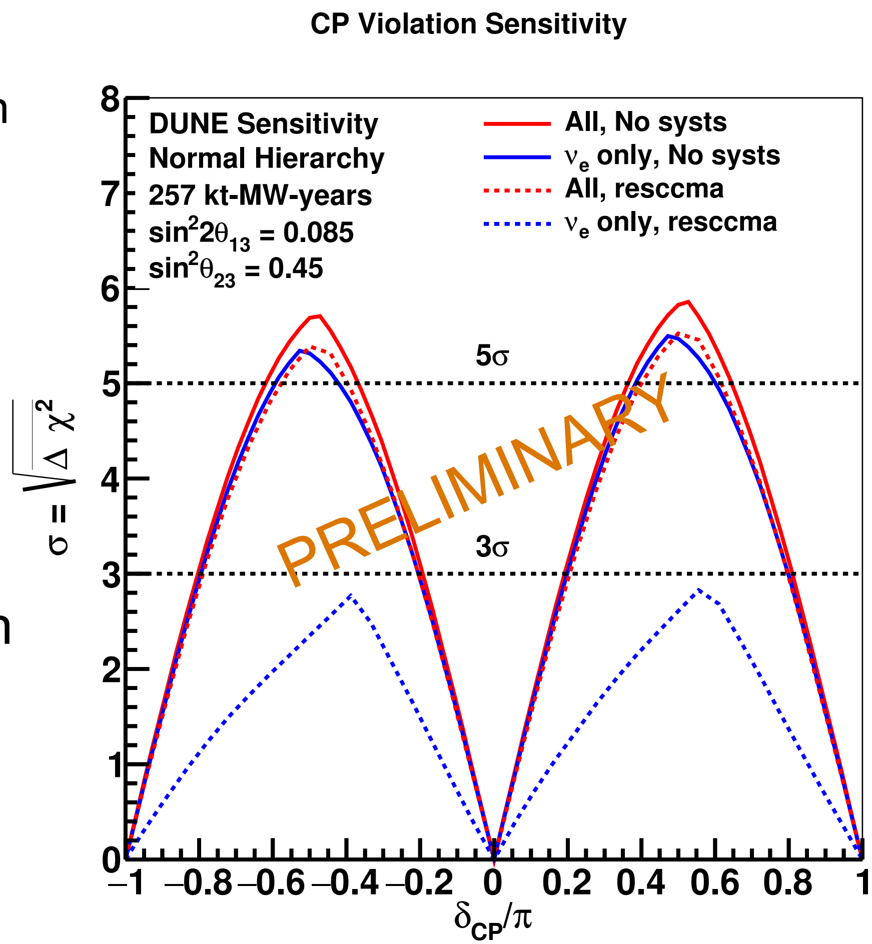


STUDIES OF CONSTRAINING UNCERTAINTY WITH FAR DETECTOR SAMPLES

Warning: rather detailed, preliminary

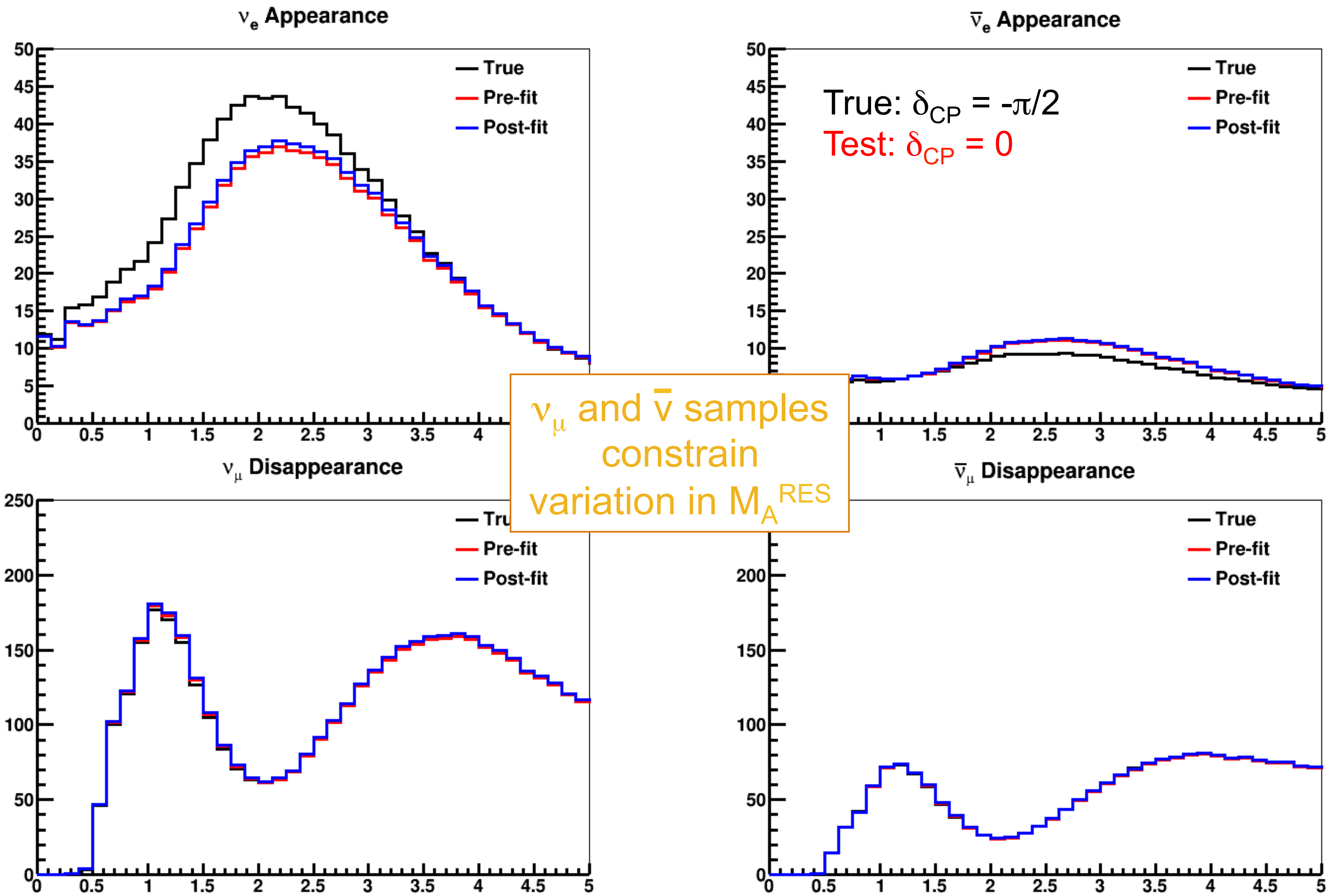
FD Interaction Constraints

- FastMC with **no** ND constraints
  - Vary cross-section parameters within GENIE uncertainties
    - eg: M_A^{RES}
- Significant degradation in sensitivity for fit to only ν_e appearance sample for a single cross-section systematic uncertainty
- Fit to all four FD samples constrains cross-section variations reducing degradation in sensitivity for same cross-section uncertainty
- Includes uncertainty in cross-section ratios:
  - $\nu/\bar{\nu}$ (10%)
  - ν_e/ν_μ (2.5%)
  - Measurements and theoretical input needed



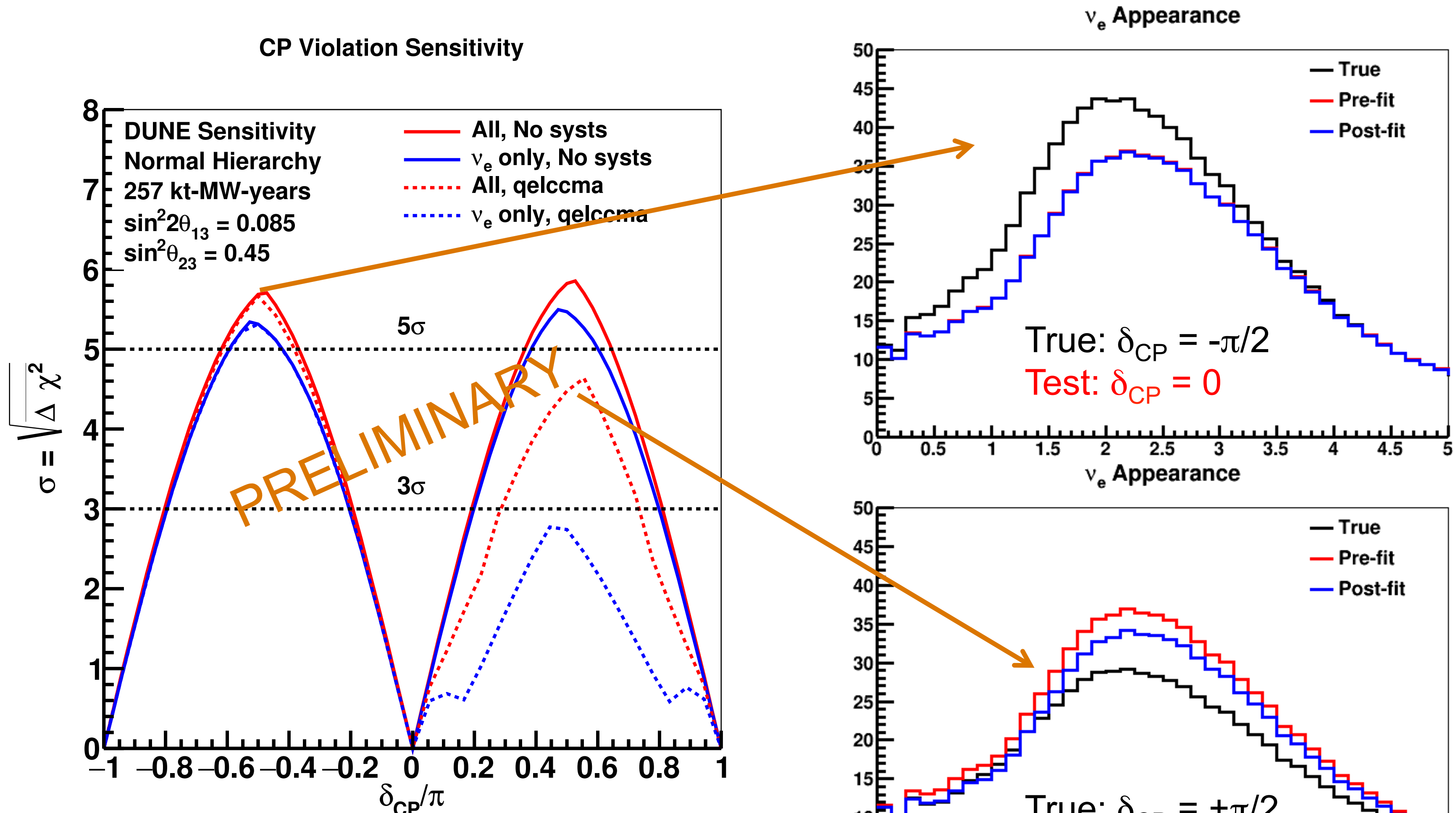
For illustration only – oscillation uncertainties not included!

FD Interaction Constraints



ν_μ and $\bar{\nu}$ samples constrain variation in M_A^{RES}

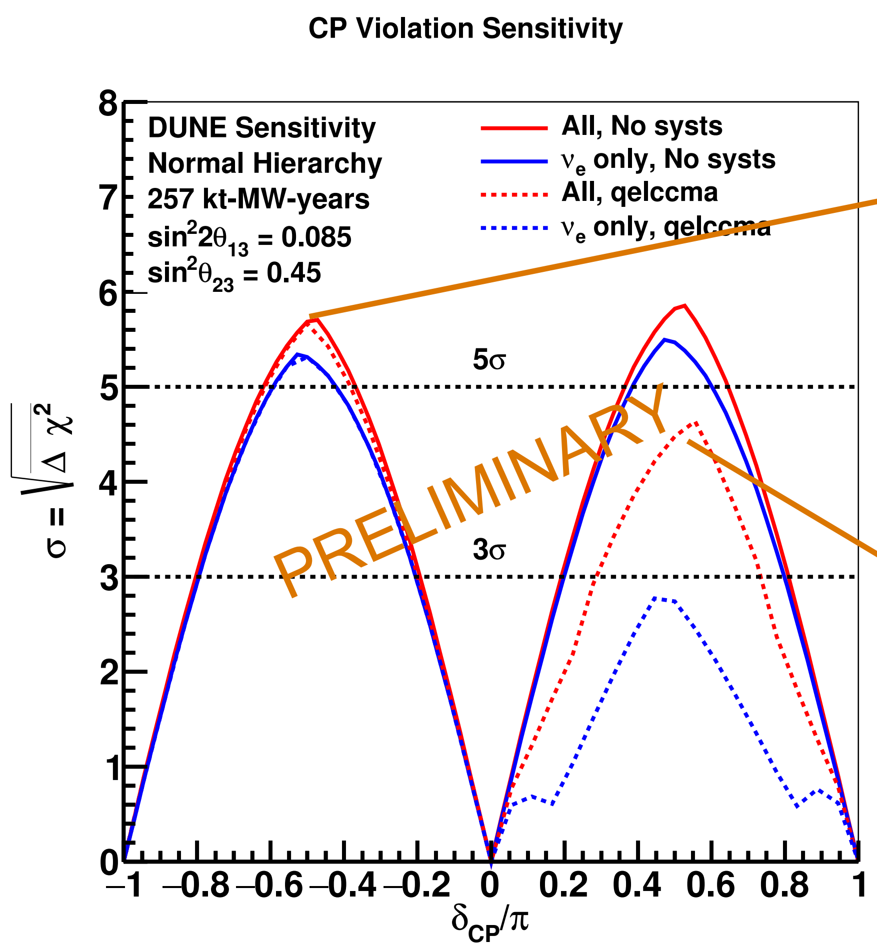
FD Interaction Constraints

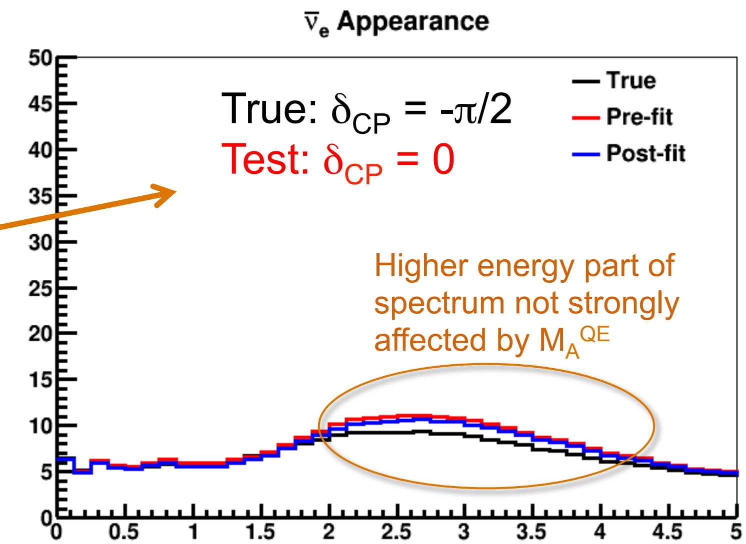


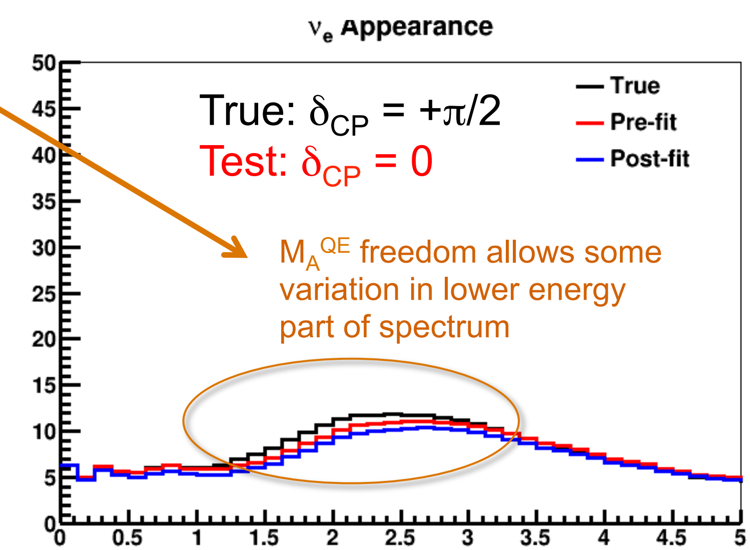
For M_A^{QE}, better constraint for $\delta_{CP} = -\pi/2$ than for $\delta_{CP} = +\pi/2$

FD Interaction Constraints

DEEP UNDERGROUND NEUTRINO EXPERIMENT



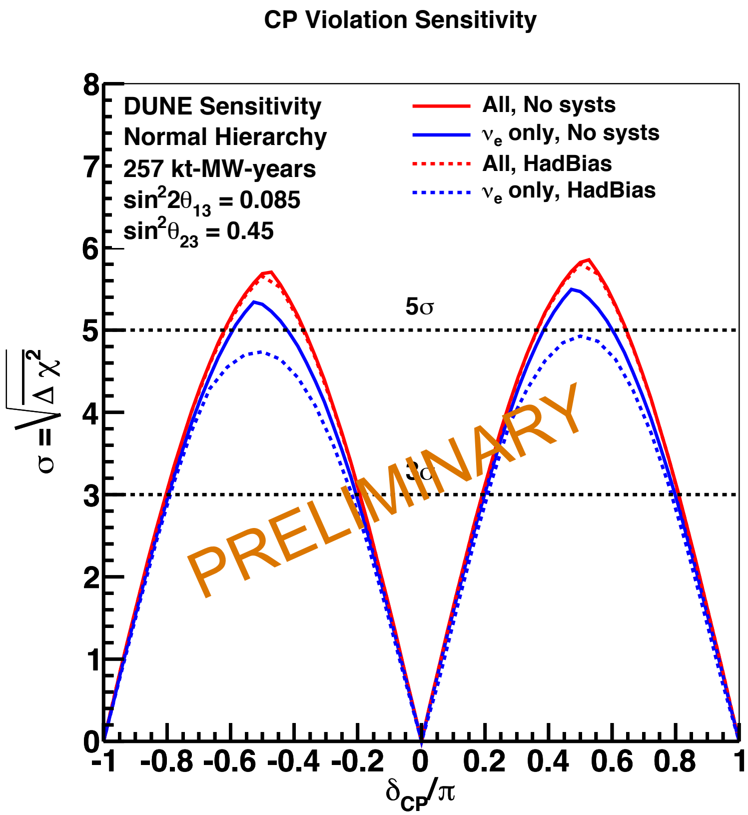




For M_A^{QE}, better constraint for $\delta_{CP} = -\pi/2$ than for $\delta_{CP} = +\pi/2$

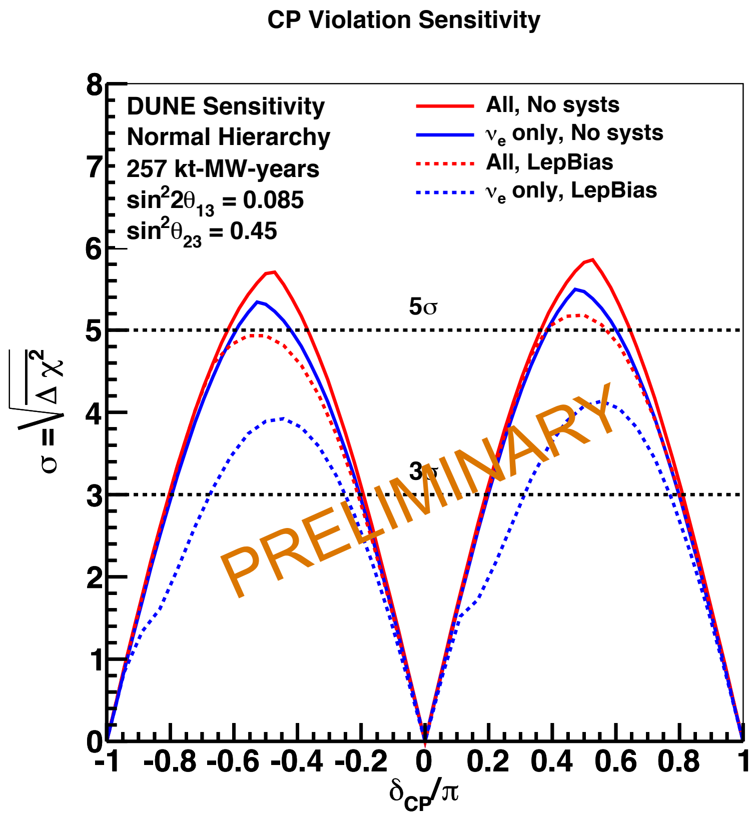
Examples of Constraining Detector Effects With FD Data

Bias in Hadron Energy:



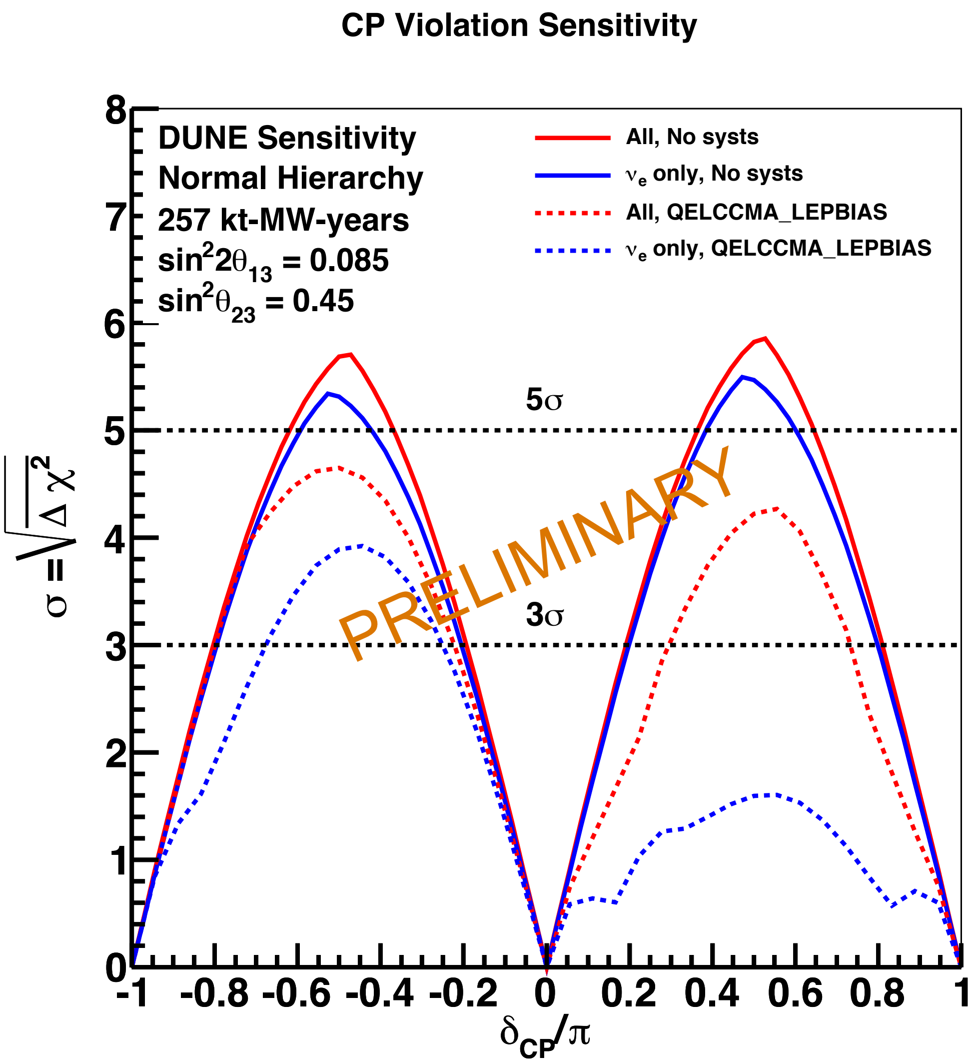
Assumes 20% bias in neutron energy and significant correlation between hadron energy scales for ν_μ and ν_e. Work ongoing.

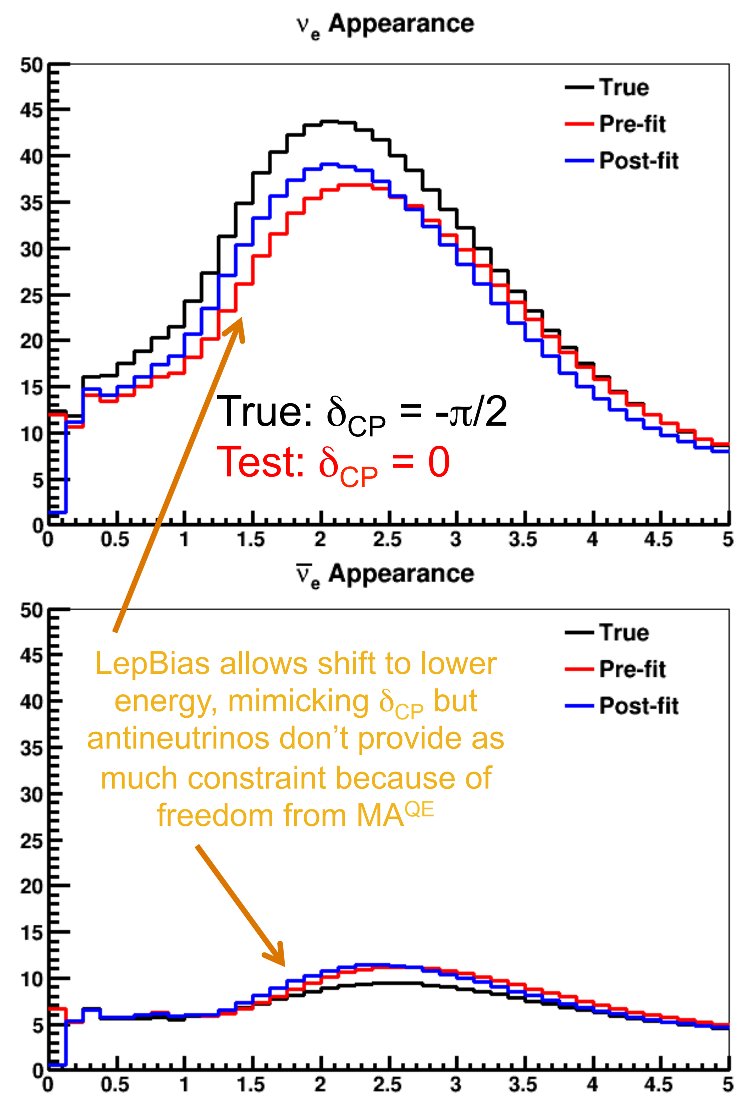
Bias in Lepton Energy:



Assumes 3% bias in lepton energy and no correlation between lepton energy scales for ν_μ and ν_e.

Combining Effect of M_A^{QE} & Lepton Energy Bias





Summary of FD Studies

- Ability of far detector samples to constrain uncertainty from cross-sections and detector effects depends on assumed correlation of these effects among the four FD samples
- Significant reduction in sensitivity degradation when considering four-sample fit relative to neutrino-only fit
- Combination of cross-section and detector effects important to consider

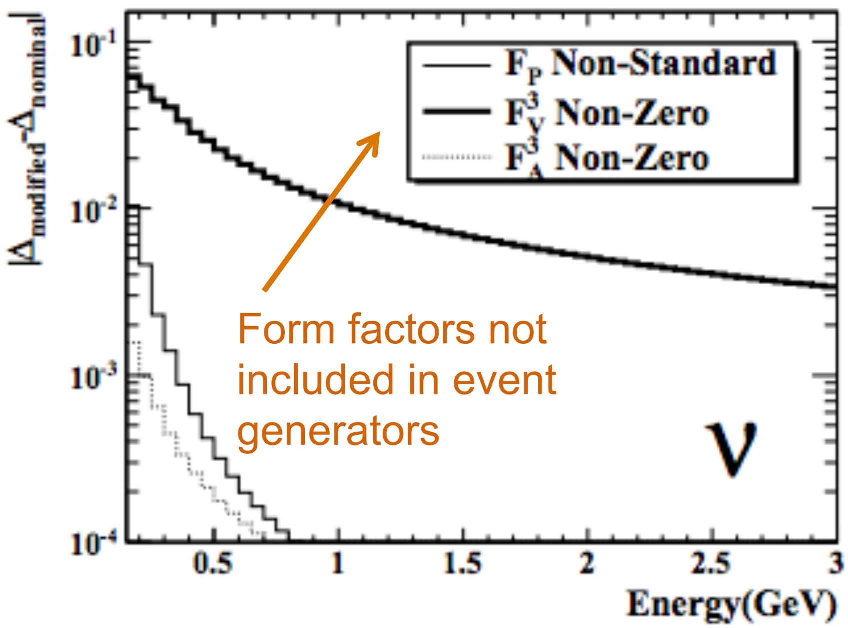
WHAT DOES DUNE NEED FROM THE NuInt COMMUNITY?

My personal perspective…

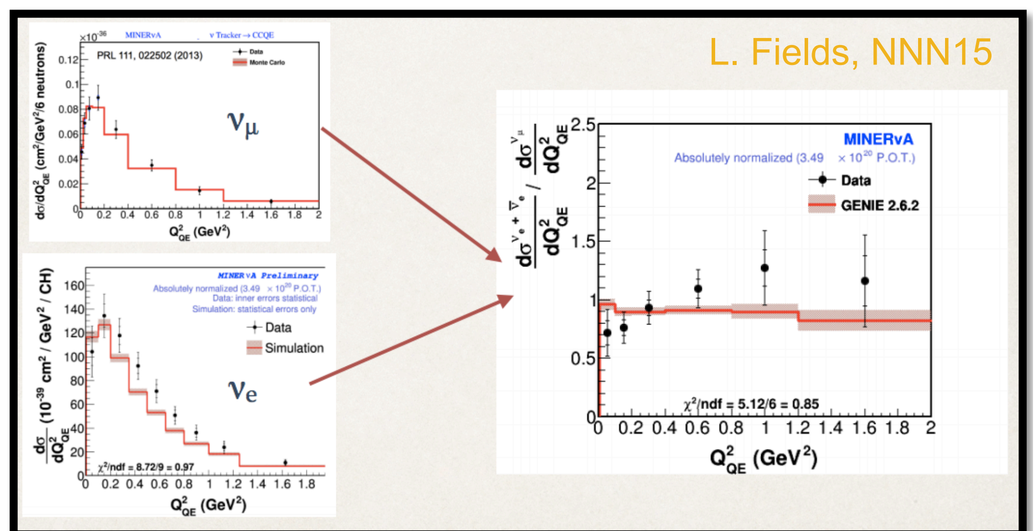
Constraints on Cross-Section Ratios

- Theoretical and experimental constraints on variation in $\nu/\bar{\nu}$ and ν_e/ν_μ cross-section ratios determines how much four far-detector samples can constrain uncertainty from cross-section models
  - Current nominal variation for DUNE studies is 10% for $\nu/\bar{\nu}$ and 2.5% for ν_e/ν_μ
  - Even a consensus on the right order of magnitude for these uncertainties would be valuable

arXiv:1206.6745



MINERvA CCQE
arXiv:1509.05729



Collaboration between Event Generators and Experiments

- Alternative models are being implemented in generators
  - Example: GENIE 2.10.0 release notes announce optional models:
    - Effective spectral function model (Bodek, Christy, Coopersmith)
    - Resonant pion model (Berger, Sehgal)
- Guidance needed to make self-consistent use of alternative models and fair comparisons among models
  - What self-consistent set(s) of models/tunes are available?
- Balance between desire of experiments to “own” the generator for quick studies and desire of generator collaborations to include new models as part of official releases with appropriate tuning

Summary

- Systematic uncertainty at the level of a few percent required for DUNE discovery of CP violation
- DUNE experiment strategy to control systematic uncertainty includes:
  - High performance near and far detectors providing ability to constrain systematics using DUNE data ★
  - External measurements and calibration data
  - Improved modeling of neutrino interactions
- Understanding of neutrino interactions and LArTPC detectors is a worldwide effort, being undertaken by and affecting the whole neutrino community.
  - Short- and long-baseline oscillation experiments
  - Neutrino interaction and hadron production measurements
  - Detector prototype and calibration measurements
  - Detector development efforts
  - Theory/modeling/event generation from neutrino and nuclear physics