DUNE STRATEGY FOR CONTROLLING SYSTEMATIC UNCERTAINTY

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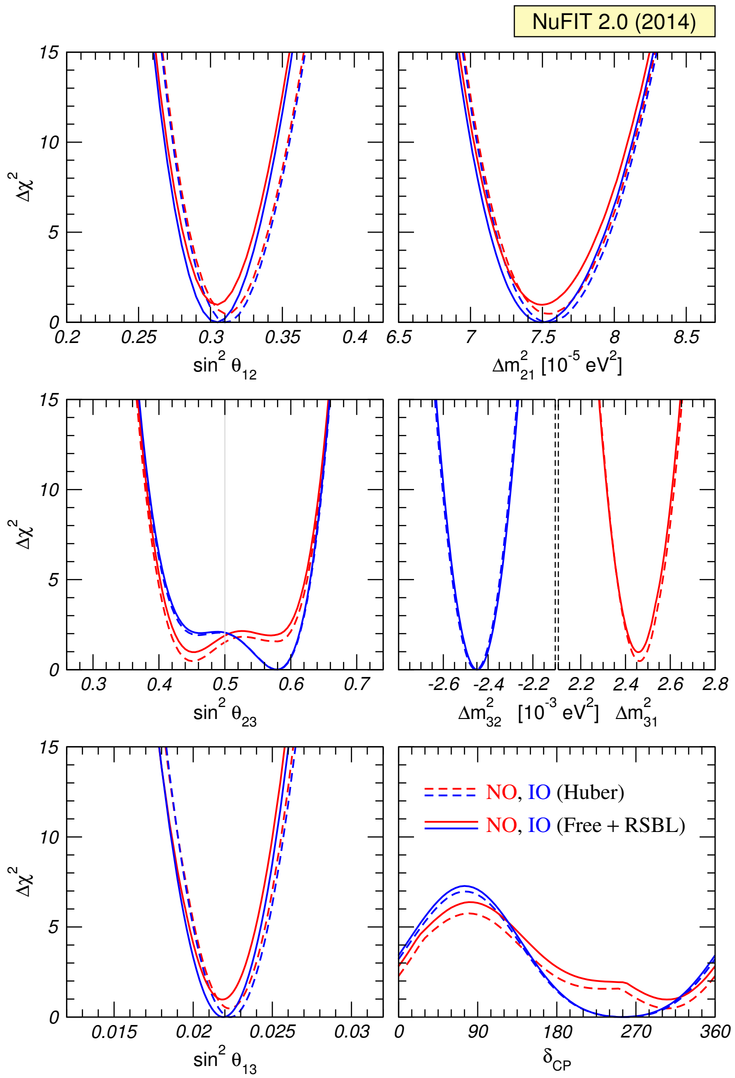
*See NNN 2015: T. Kutter for details of LBNF/DUNE

Neutrino Oscillation Parameters

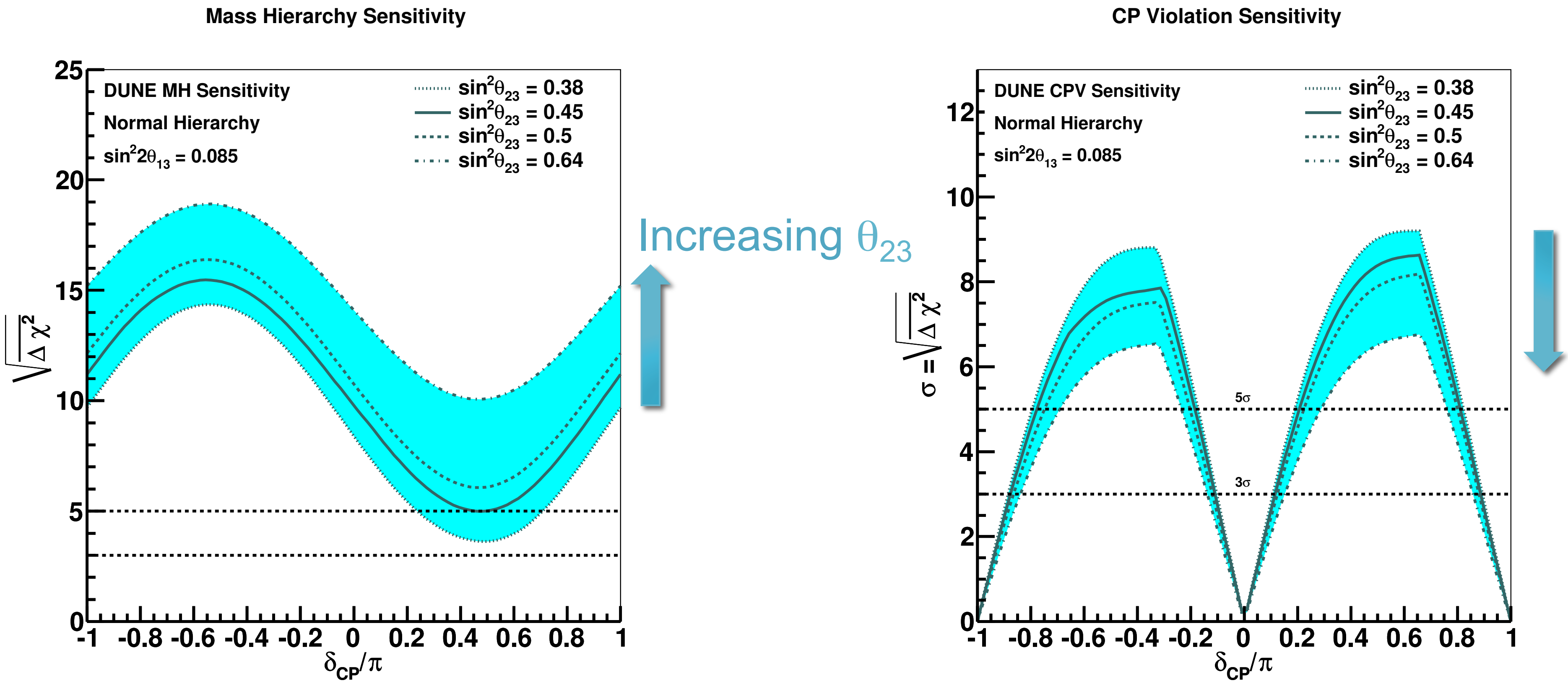
DEEP UNDERGROUND NEUTRINO EXPERIMENT



- NuFit 2014
  - http://www.nu-fit.org/
  - Includes results through NOW 2014
  - θ_{13}, θ_{12}, Δm^2_{21}, Δm^2_{32} known to ~2%-2.5%
  - θ_{23} known to ~6% (octant unknown)
- Further constraints expected from existing and planned experiments:
  - External constraints on mixing angles improve early sensitivity
  - Measurements or even hints of MH or δ_{CP} value could influence run plans
- Ultimate DUNE goals include precise measurements of θ_{13}, θ_{23}, Δm^2_{32}, and δ_{CP} for unitarity and sum rule tests

Effect of θ_{23} Uncertainty

DUNE CDR:



$$\mathcal{A}_{CP} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{CP}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right) + \text{matter effects}$$

Simple Systematics Treatment

- 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.

Anticipated Uncertainties

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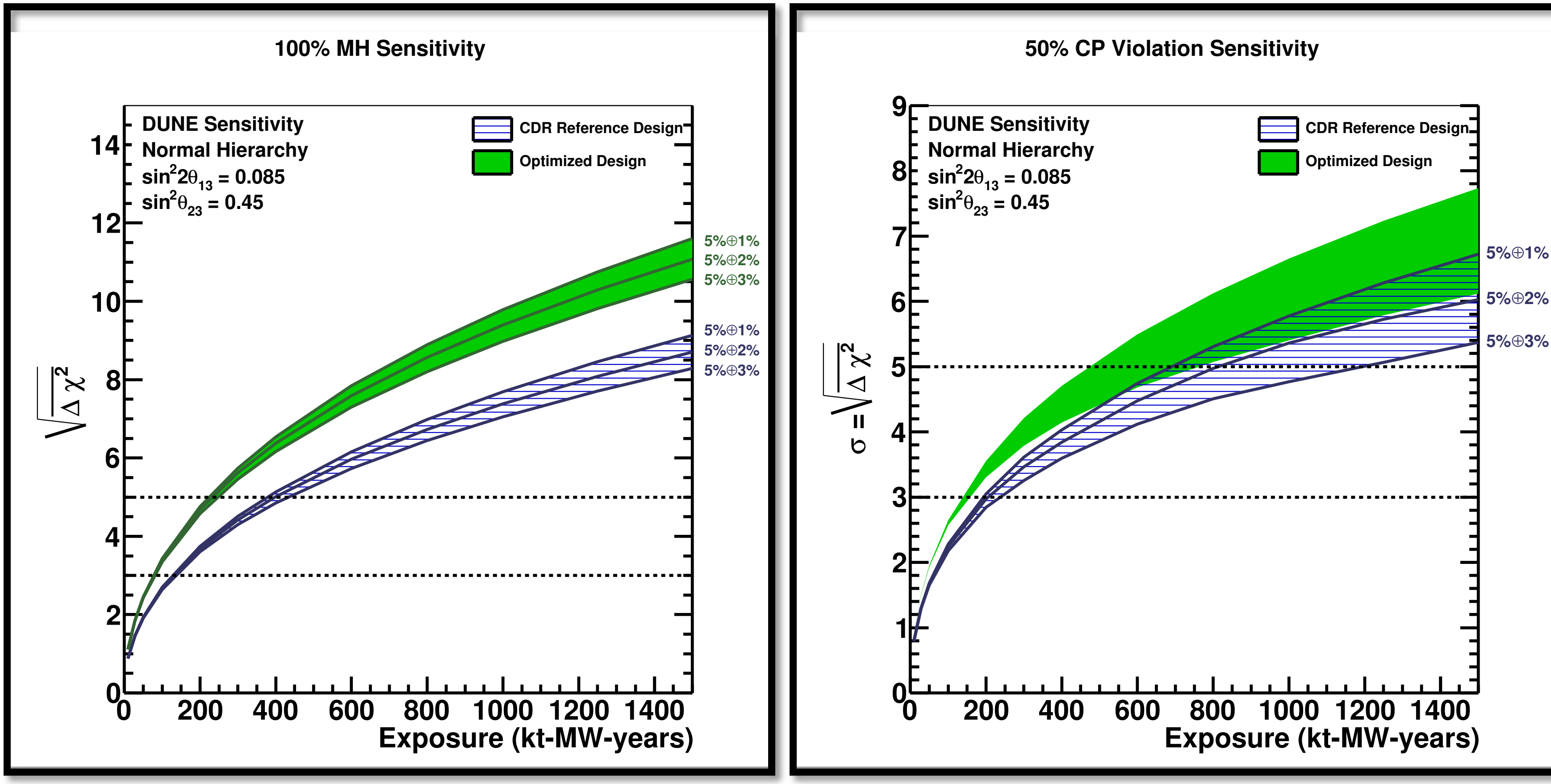
Source of Uncertainty	MINOS ν_e	T2K ν_e	Goal for DUNE ν_e
Beam Flux	0.3%	3.2%	2%
Interaction Model	2.7%	5.3%	~2%
Energy Scale (ν_μ)	3.5%	Included above	(2%) included in 5% ν_μ uncertainty
Energy Scale (ν_e)	2.7%	2.5% includes all FD effects	2%
Fiducial Volume	2.4%	1%	1%
Total Uncertainty	5.7%	6.8%	3.6%
Used in DUNE sensitivity calculations:			5% $\oplus$ 2%

DUNE goals are for the *total* normalization uncertainty on the ν_e appearance sample. The DUNE analysis will be a 3-flavor oscillation fit such that uncertainties correlated among the four FD samples will largely cancel.

Effect of Systematics

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 Near Detector

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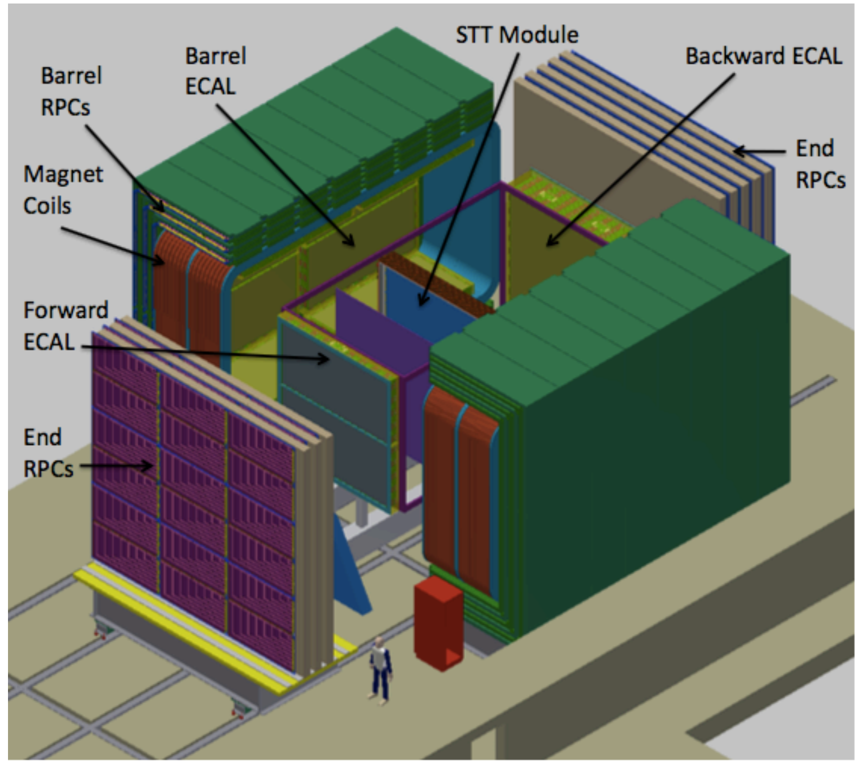
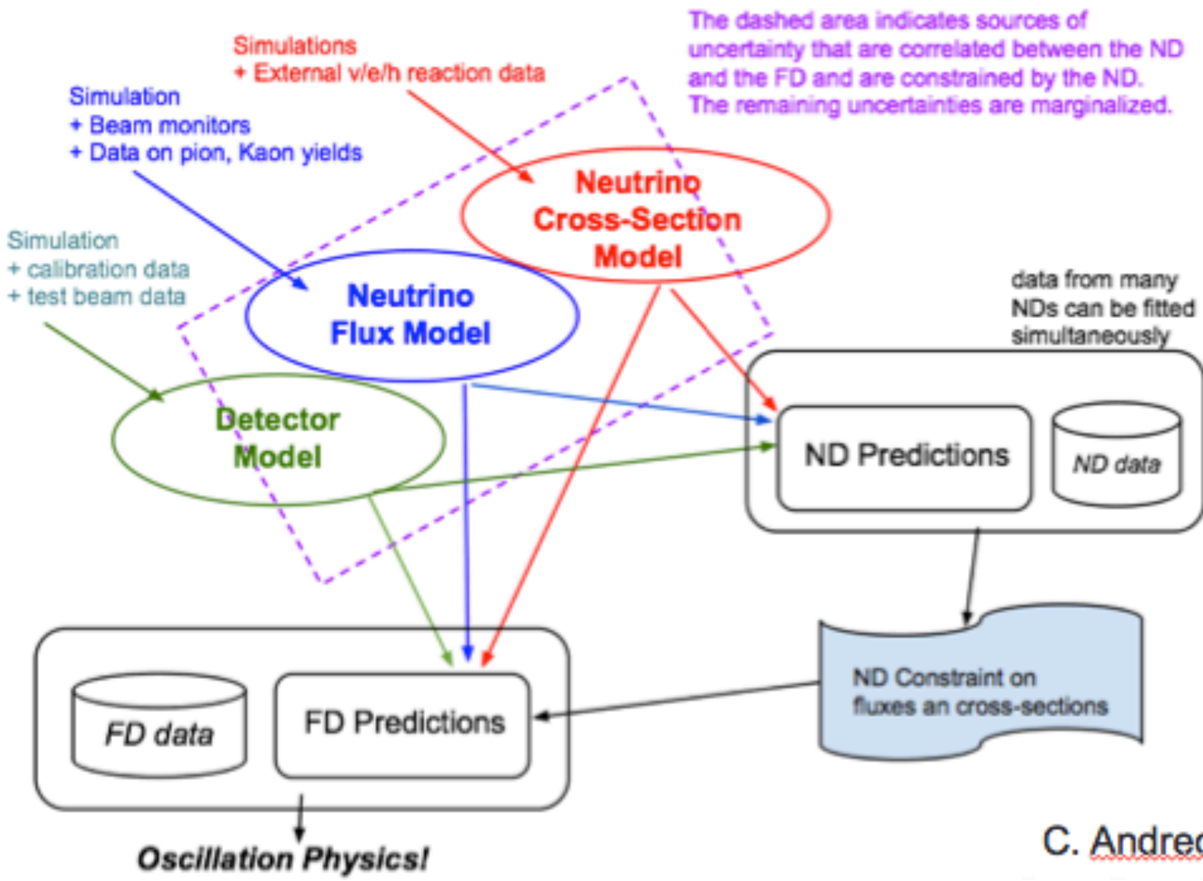
- Near detector critical for constraining systematic uncertainty
- Ability to isolate neutrino interactions on argon required
- DUNE ND optimization task force evaluating ND options including a fine-grained tracker, a liquid argon TPC, a gaseous argon TPC, and combinations or new ideas
- CDR reference design is the fine-grained tracker:
  - Straw-tube tracker
  - EM calorimeter
  - 0.4-T dipole magnet
  - Muon detectors
  - Variety of nuclear targets, *including argon*

DUNE ND Reference Design:



Example of Analysis Strategy

- T2K-like strategy is a good starting point:



C. Andreopoulos

Strategy for Flux

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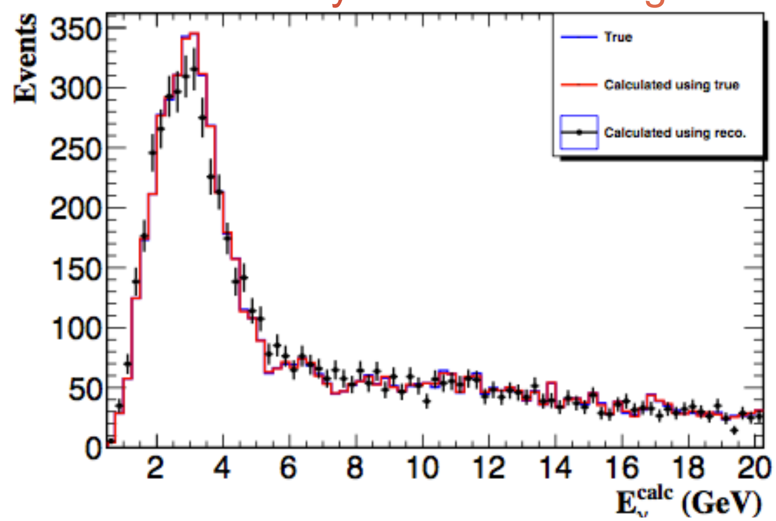
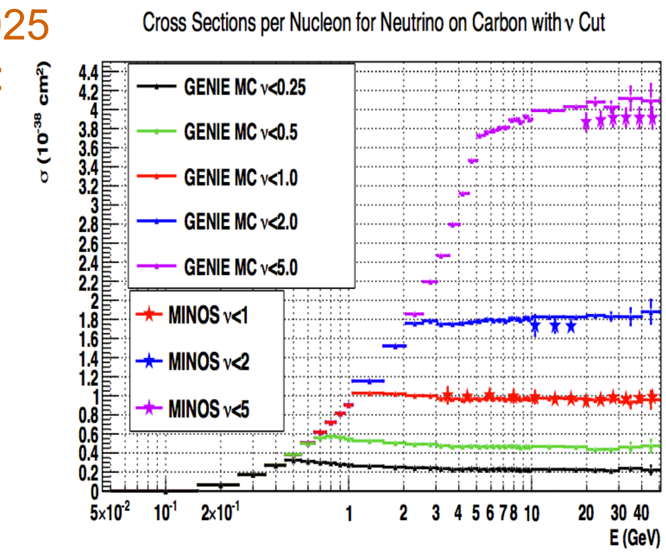
- Constrain absolute flux with near detector measurements of fully-leptonic neutrino interactions
  - Cross-sections known to high precision
  - Neutrino-electron scattering: ~3% stat. (E_ν < 5 GeV)
  - Inverse muon decay: ~3% stat. (E_ν > 11 GeV)
- Constrain flux shape using low-ν_0 method: 1-2%
- Low-ν_0 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:



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

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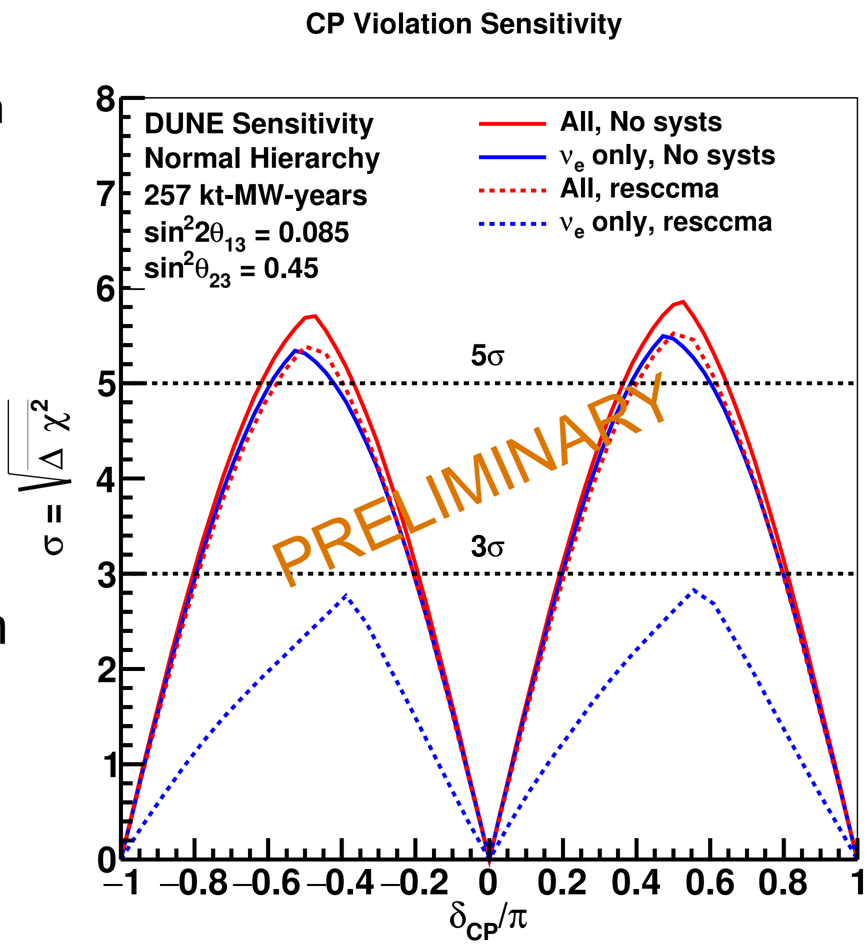
- Worldwide effort that will benefit DUNE!
- Alternative models being implemented in GENIE include:
  - Long- and short-range correlations among nucleons
  - Effect of random phase approximations
  - Meson exchange currents
  - 2p-2h effects in CCQE
  - Effective spectral functions
  - Coherent pion production
  - Alternative model of DIS interactions
  - Variation of tunable parameters within existing models
- Comparisons among generators
  - GENIE, NuWro, GiBUU, FLUKA
- 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!

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

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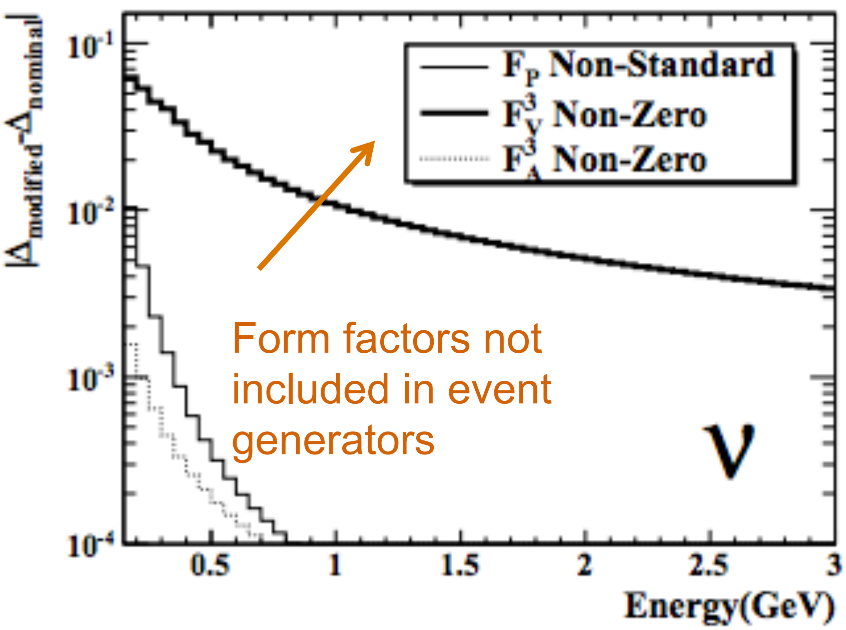
arXiv:1206.6745



Strategy for Detector Effects

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- 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
  - See NNN talks on Wednesday
- 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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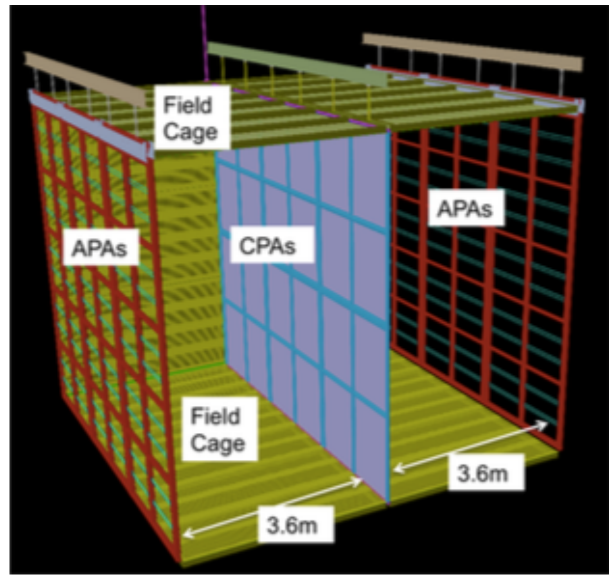
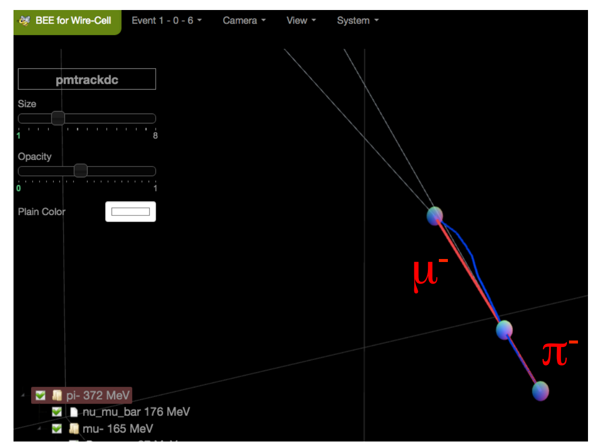
protoDUNE:



protoDUNE MC:
500 MeV pion



Examples of Constraining Detector Effects With FD Data

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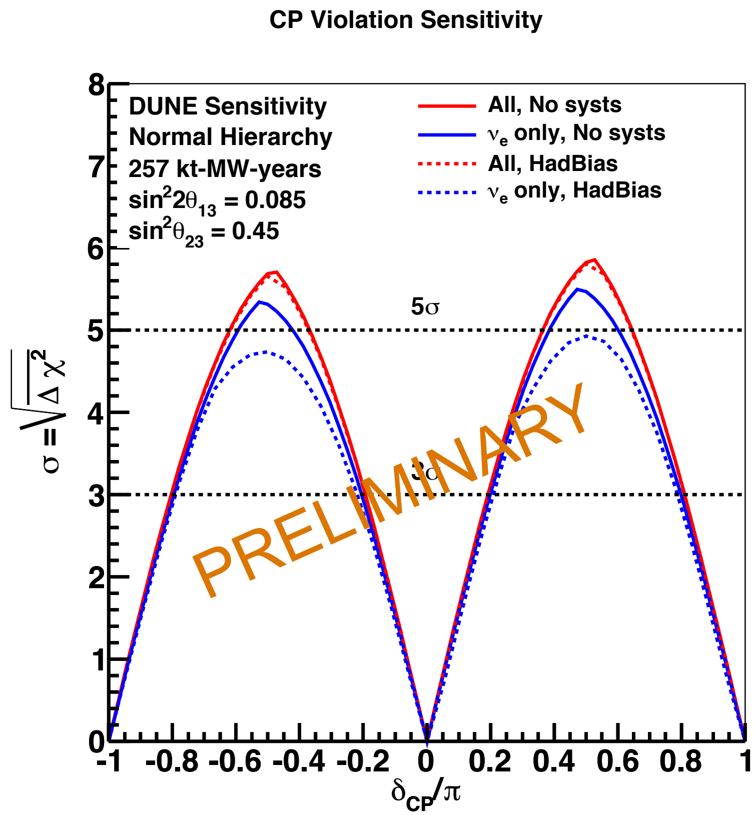
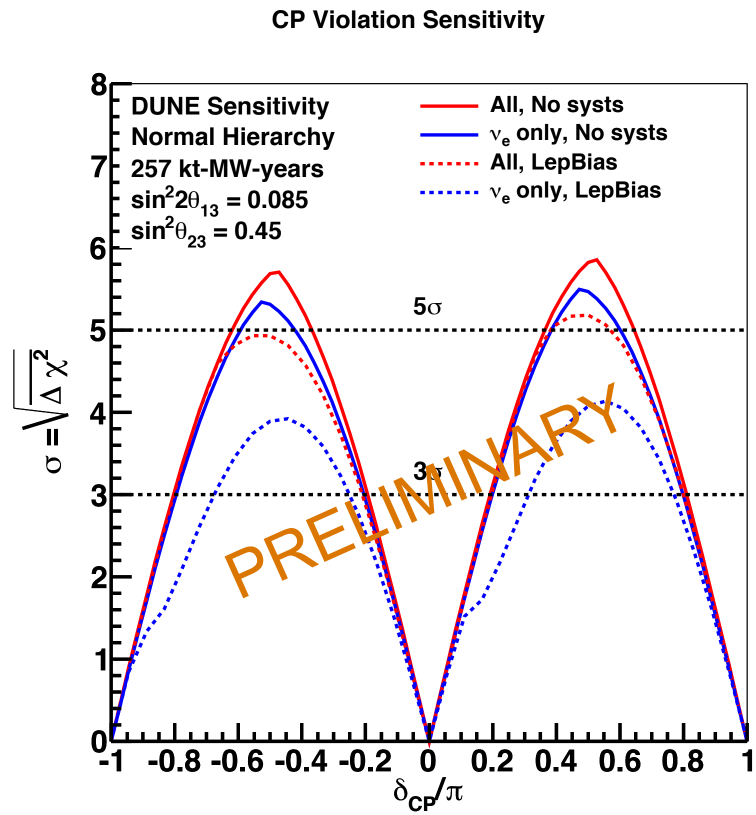
Bias in Hadron Energy:



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.

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