DEEP UNDERGROUND
NEUTRINO EXPERIMENT

SCIENTIFIC GOALS OF DUNE AND ND REQUIREMENTS

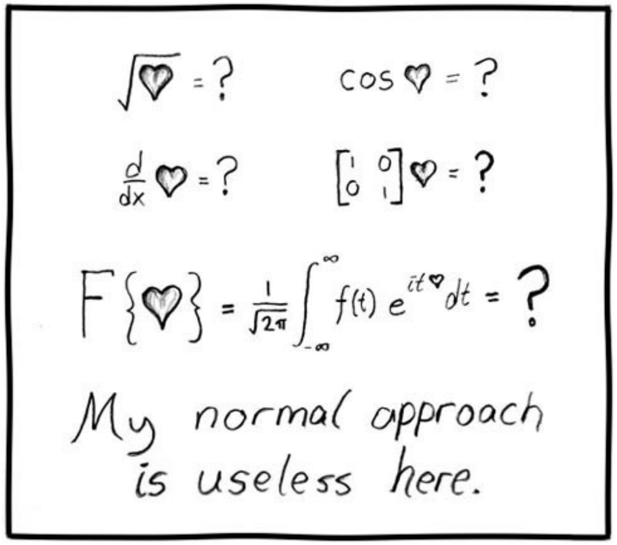
Elizabeth Worcester (BNL)
DUNE ND Workshop
March 27, 2017

Overview

- Introduction and history
- **Long-baseline physics**
  - **Sensitivity calculations**
  - **Handles on individual sources of uncertainty**
  - **Studies of systematic uncertainty & tools at our disposal**
  - **Ideas/plans for future studies**
- ND physics

Introduction

- Warning: I’m not actually going to give you any ND requirements!
  - I wish I could…
  - I’ll tell you the ways we’re working on it and the tools we have at our disposal...
  - Will try to point out discussion topics that I think are important to guide our decision making



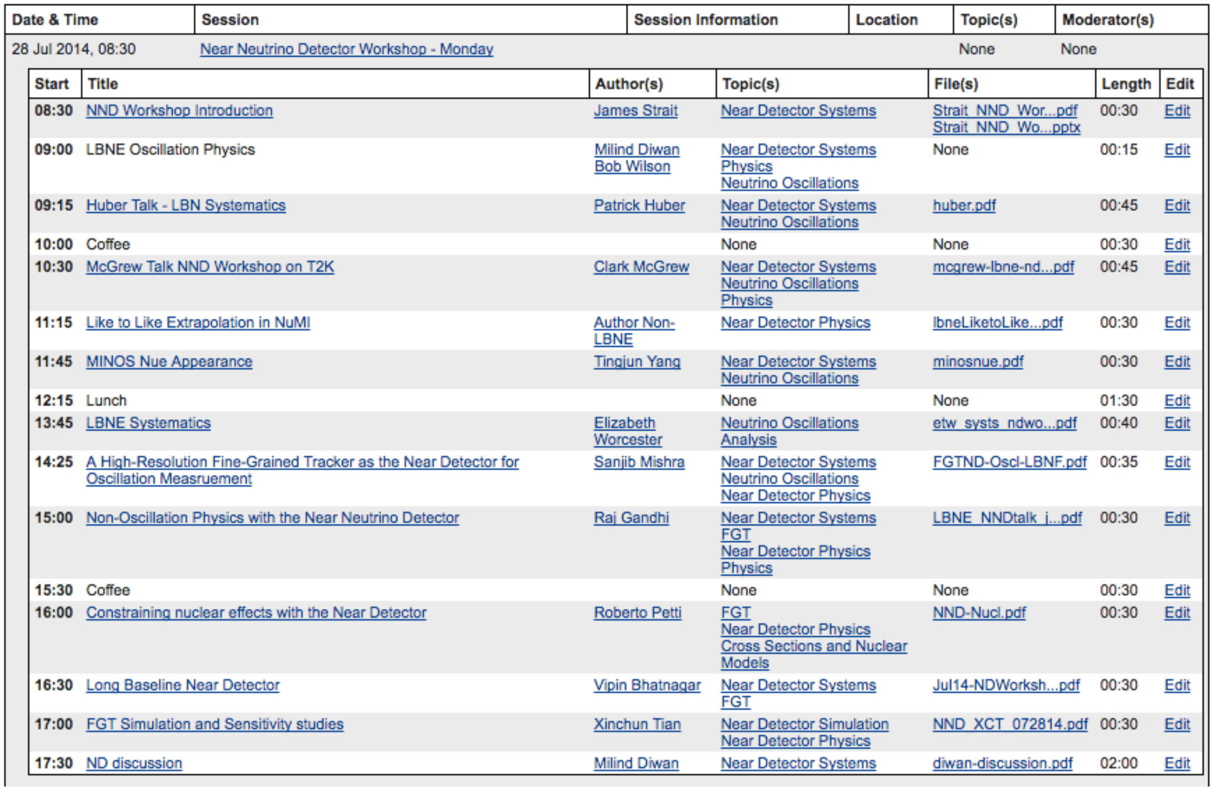
(just replace the ♥ with DUNE systematics…)

History

(I feel like we've been here before…)

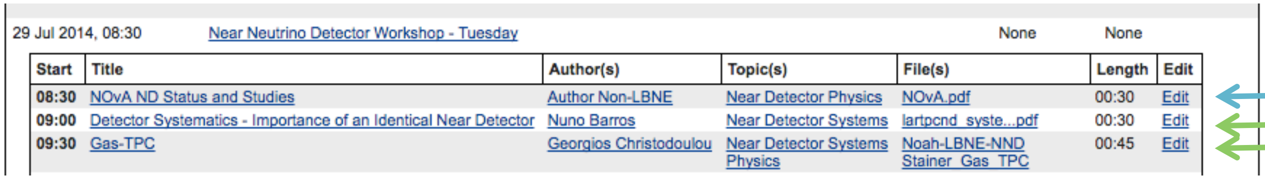
DEEP UNDERGROUND NEUTRINO EXPERIMENT

LBNE Near Detector Workshop (July 2014):
http://lbne2-docdb.fnal.gov:8080/cgi-bin/DisplayMeeting?conferenceid=1041



Date & Time	Session	Session Information	Location	Topic(s)	Moderator(s)
28 Jul 2014, 08:30	Near Neutrino Detector Workshop - Monday			None	None

Start	Title	Author(s)	Topic(s)	File(s)	Length	Edit
08:30	NND Workshop Introduction	James Strait	Near Detector Systems	Strait_NND_Wor...pdf Strait_NND_Wo...pptx	00:30	Edit
09:00	LBNE Oscillation Physics	Milind Diwan Bob Wilson	Near Detector Systems Physics Neutrino Oscillations	None	00:15	Edit
09:15	Huber Talk - LBN Systematics	Patrick Huber	Near Detector Systems Neutrino Oscillations	huber.pdf	00:45	Edit
10:00	Coffee		None	None	00:30	Edit
10:30	McGrew Talk NND Workshop on T2K	Clark McGrew	Near Detector Systems Neutrino Oscillations Physics	mcgrew-lbne-nd...pdf	00:45	Edit
11:15	Like to Like Extrapolation in NuMI	Author Non-LBNE	Near Detector Physics	lbneLiketoLike...pdf	00:30	Edit
11:45	MINOS Nue Appearance	Tingjun Yang	Near Detector Systems Neutrino Oscillations	minosnue.pdf	00:30	Edit
12:15	Lunch		None	None	01:30	Edit
13:45	LBNE Systematics	Elizabeth Worcester	Neutrino Oscillations Analysis	etw_systs_ndwo...pdf	00:40	Edit
14:25	A High-Resolution Fine-Grained Tracker as the Near Detector for Oscillation Measruement	Sanjib Mishra	Near Detector Systems Neutrino Oscillations Near Detector Physics	FGTND-Oscl-LBNF.pdf	00:35	Edit
15:00	Non-Oscillation Physics with the Near Neutrino Detector	Raj Gandhi	Near Detector Systems FGT Near Detector Physics Physics	LBNE_NNDtalk_j...pdf	00:30	Edit
15:30	Coffee		None	None	00:30	Edit
16:00	Constraining nuclear effects with the Near Detector	Roberto Petti	FGT Near Detector Physics Cross Sections and Nuclear Models	NND-Nucl.pdf	00:30	Edit
16:30	Long Baseline Near Detector	Vipin Bhatnagar	Near Detector Systems FGT	Jul14-NDWorksh...pdf	00:30	Edit
17:00	FGT Simulation and Sensitivity studies	Xinchun Tian	Near Detector Simulation Near Detector Physics	NND_XCT_072814.pdf	00:30	Edit
17:30	ND discussion	Milind Diwan	Near Detector Systems	diwan-discussion.pdf	02:00	Edit



29 Jul 2014, 08:30	Near Neutrino Detector Workshop - Tuesday	None	None

Start	Title	Author(s)	Topic(s)	File(s)	Length	Edit
08:30	NOvA ND Status and Studies	Author Non-LBNE	Near Detector Physics	NOvA.pdf	00:30	Edit
09:00	Detector Systematics - Importance of an Identical Near Detector	Nuno Barros	Near Detector Systems	lartpcnd_syste...pdf	00:30	Edit
09:30	Gas-TPC	Georgios Christodoulou	Near Detector Systems Physics	Noah-LBNE-NND Stainer_Gas_TPC	00:45	Edit

Oscillation physics

Systematics

T2K experience

NuMI experience

NuMI experience

Systematics

FGT

ND Physics

Systematics

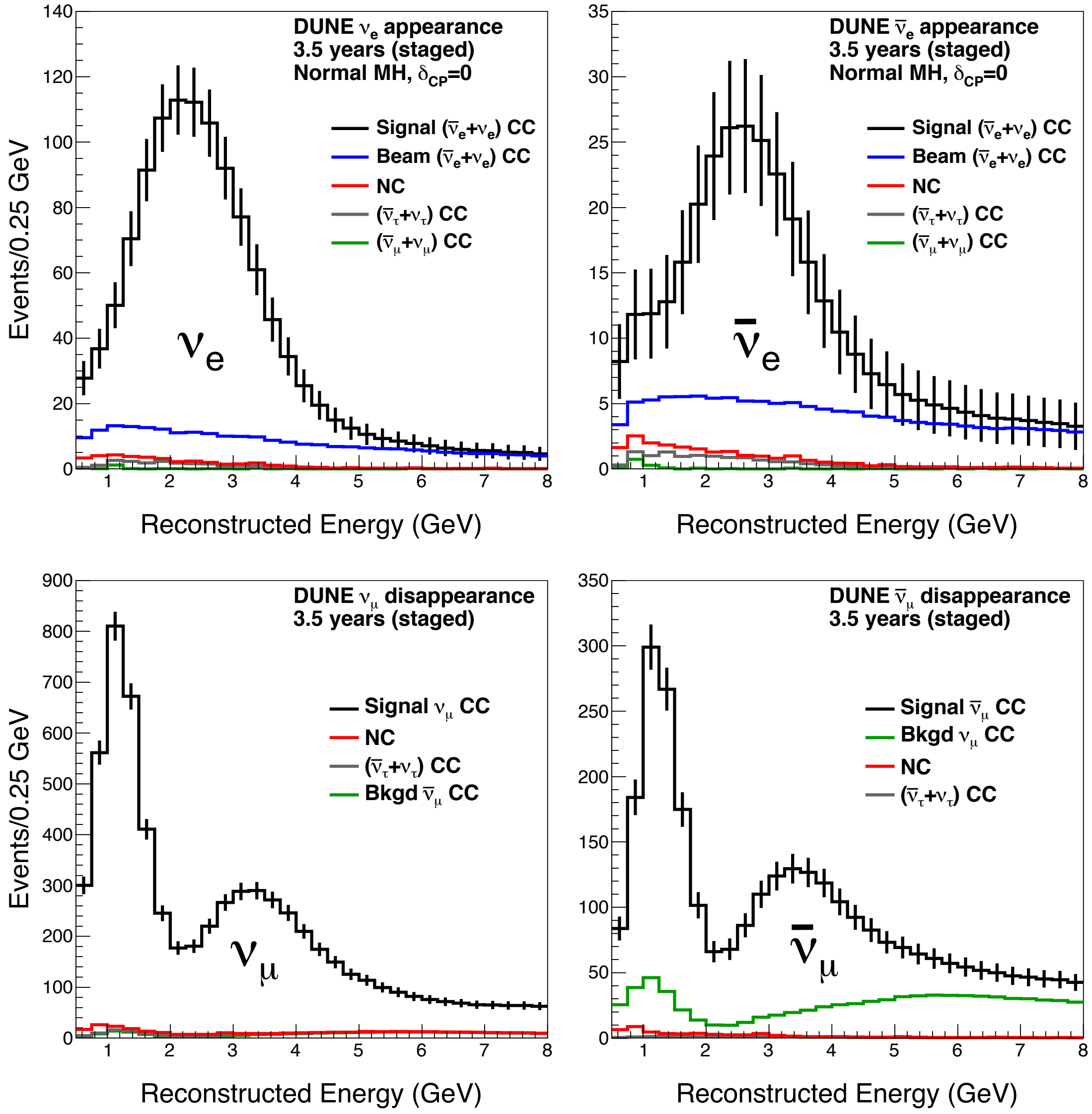
FGT

FGT

NOvA plans

Argon NDs

Oscillation Sensitivity Calculations



- Public calculations:
- GLoBES-based fit to four FD samples
- Neutrino beam flux simulated using GEANT4
- GENIE event generator
- Reconstructed spectra predicted using detector response parameterized at the single particle level
- Order 1000 ν_e appearance events in ~7 years of equal running in neutrino and antineutrino mode
- Simple systematics treatment
- GLoBES configurations arXiv:1606.09550

MH & CPV Sensitivity

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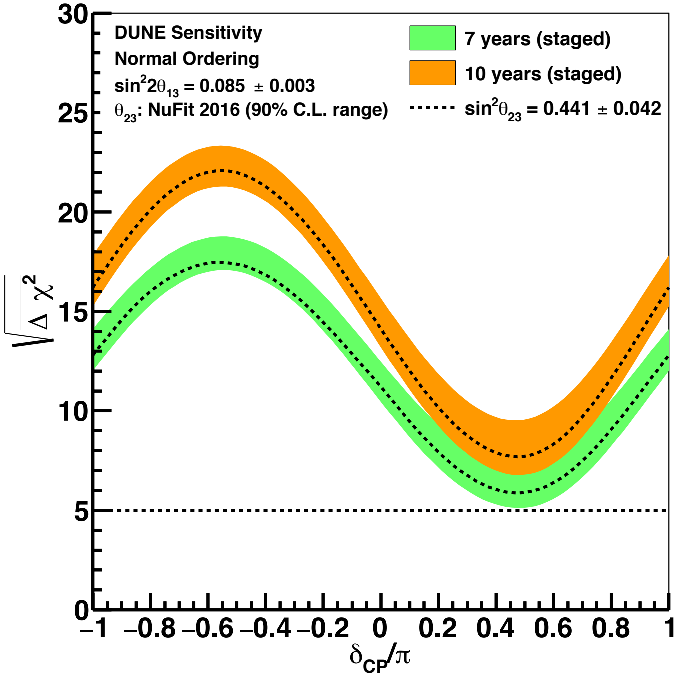
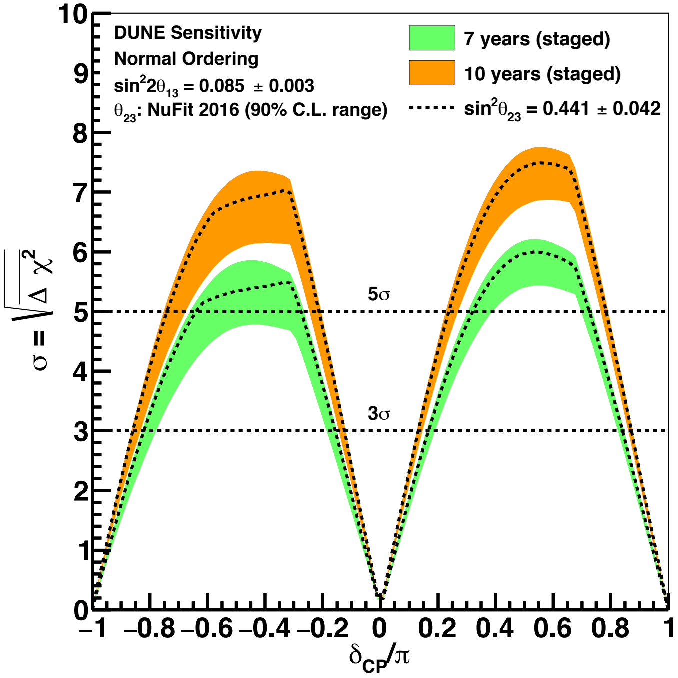
NEUTRINO EXPERIMENT

Mass Hierarchy



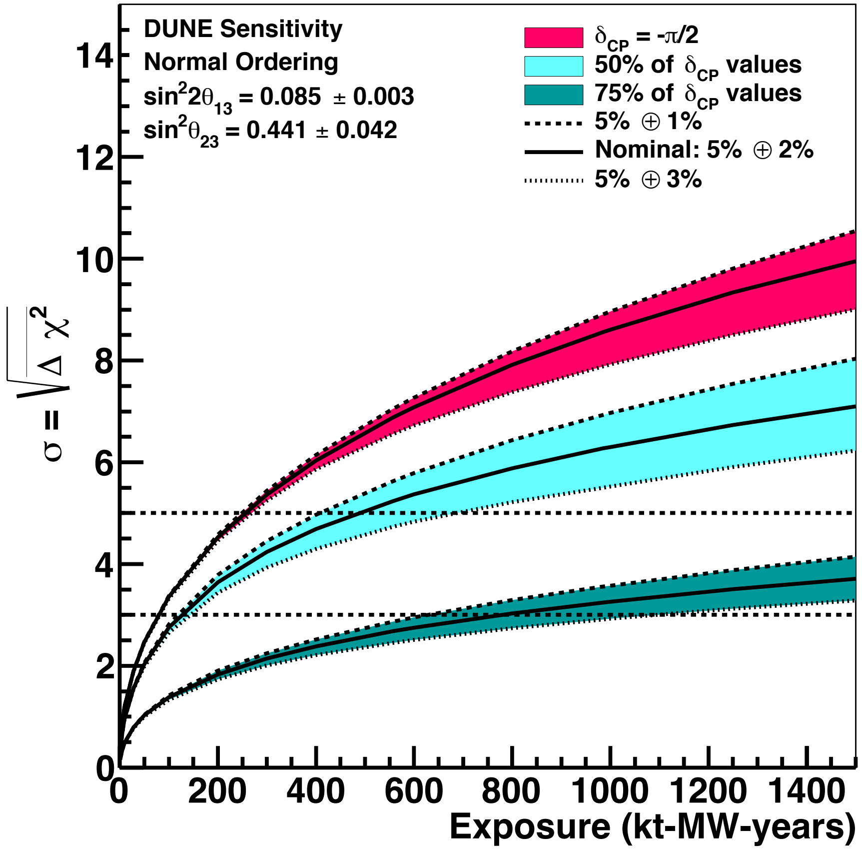
CP Violation



- Width of band indicates variation in sensitivity for θ_{23} values in the NuFit 2016 90% C.L. range (www.nu-fit.org)
- Assumes equal running in neutrino and antineutrino mode
- Includes simple normalization systematics and oscillation parameter variations

Systematics Treatment

CP Violation Sensitivity



- CPV measurement statistically limited for ~100 kt-MW-years
- Sensitivities in DUNE CDR are based on GLoBES calculations in which the effect of systematic uncertainty is approximated using uncorrelated signal normalization uncertainties to approximate residual uncertainty after all constraints from ND and other samples.
  - $\nu_\mu = \bar{\nu}_\mu = 5\%$
  - $\nu_e = \bar{\nu}_e = 2\%$
- Uncertainty in ν_e appearance sample normalization must be ~5% ⊕ 2% to discover CPV in a timely manner unless we are lucky with true δ_{CP}
- Studies varying ν_μ and background normalization uncertainties show little impact

Anticipated DUNE Uncertainty

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	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.

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Energy Sca		ffects	2%
		1%	1%
	5.7%	6.8%	3.6%
U d in DUNE sensitivity calculations:			5% ⊕ 2%

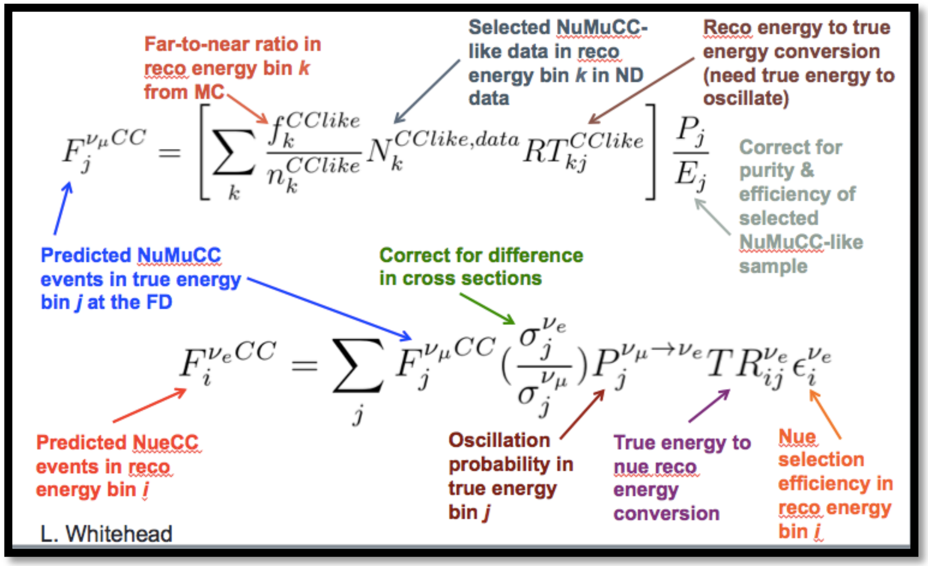
Reasonable to disagree on details – these are just goals/educated guesses. Important message is that we expect contributions on the order of 1-2% from a number of sources – no one dominant source of uncertainty. Counting on some cancellation of uncertainties among FD samples.

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.

Analysis Strategies

- See talks on MINOS/NOvA analyses from M. Sanchez and on T2K analysis from K. Mahn

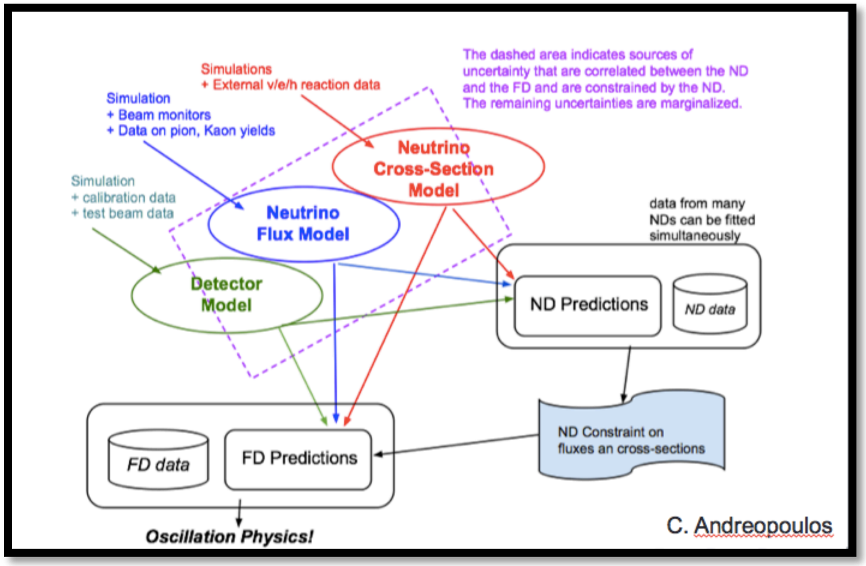
MINOS:



$$F_j^{\nu_\mu CC} = \left[\sum_k \frac{f_k^{CClike}}{n_k^{CClike}} N_k^{CClike,data} RT_{kj}^{CClike} \right] \frac{P_j}{E_j}$$

$$F_i^{\nu_e CC} = \sum_j F_j^{\nu_\mu CC} (\frac{\sigma_j^{\nu_e}}{\sigma_j^{\nu_\mu}}) P_j^{\nu_\mu \rightarrow \nu_e} TR_{ij}^{\nu_e} \epsilon_i^{\nu_e}$$

T2K:

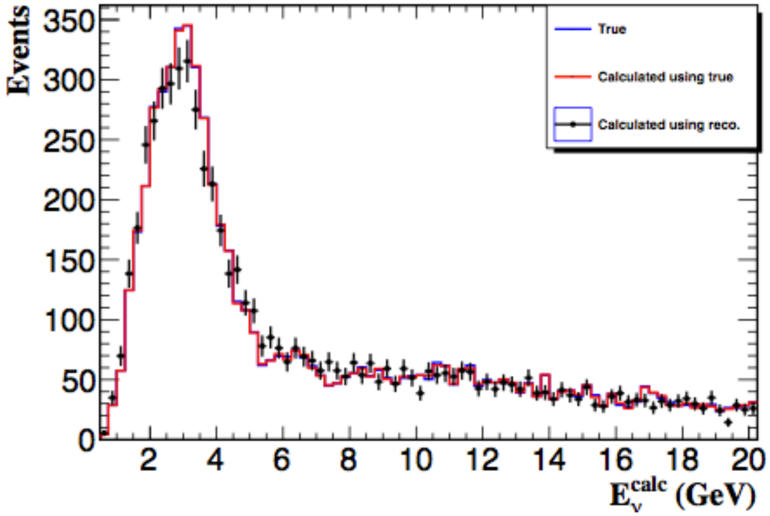


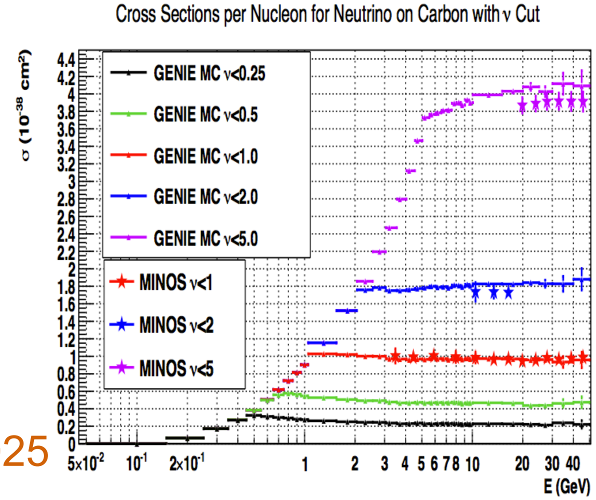
Points of discussion: Does choice of analysis strategy impact ND design choices?
Is one strategy more or less effective for different detector designs?
Or should we be able to perform either/both analyses with a well-designed ND?

Handles on 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:





arXiv:1201.3025

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- C ow-ν_0
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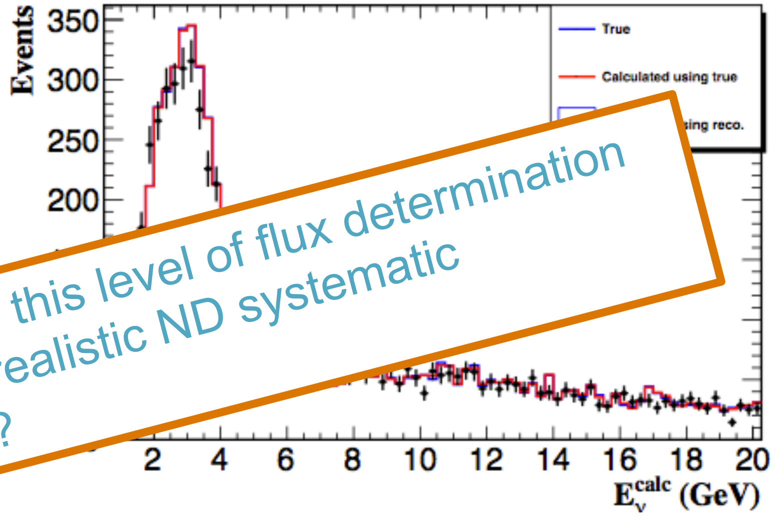
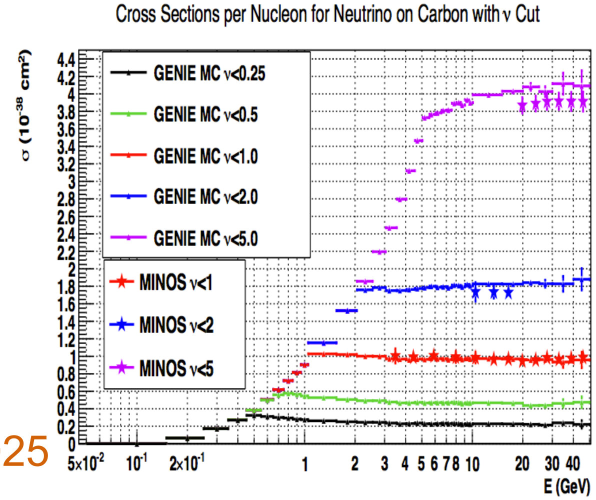
Point of discussion: How realistic is it to achieve this level of flux determination with these methods? How much do we expect realistic ND systematic uncertainties to degrade these measurements?

Fast MC study of ν-e scattering:





arXiv:1201.3025

Handles on Interaction Model

- Expect absolute uncertainties on interaction model parameters to be reduced with improved modeling and new data
- However, do not expect absolute uncertainty on interaction model to be reduced to the required few percent level: must take advantage of cancellations
  - Argon nuclear targets in ND required
  - Four FD samples allow cancellation of uncertainties that are correlated between ν_e/ν_μ or $\nu/\bar{\nu}$
  - Theoretical and experimental constraints on uncertainty 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 (and thus how good does the ND constraint need to be?)
  - Current nominal variation for DUNE studies is 10% for $\nu/\bar{\nu}$ and 2.5% for ν_e/ν_μ

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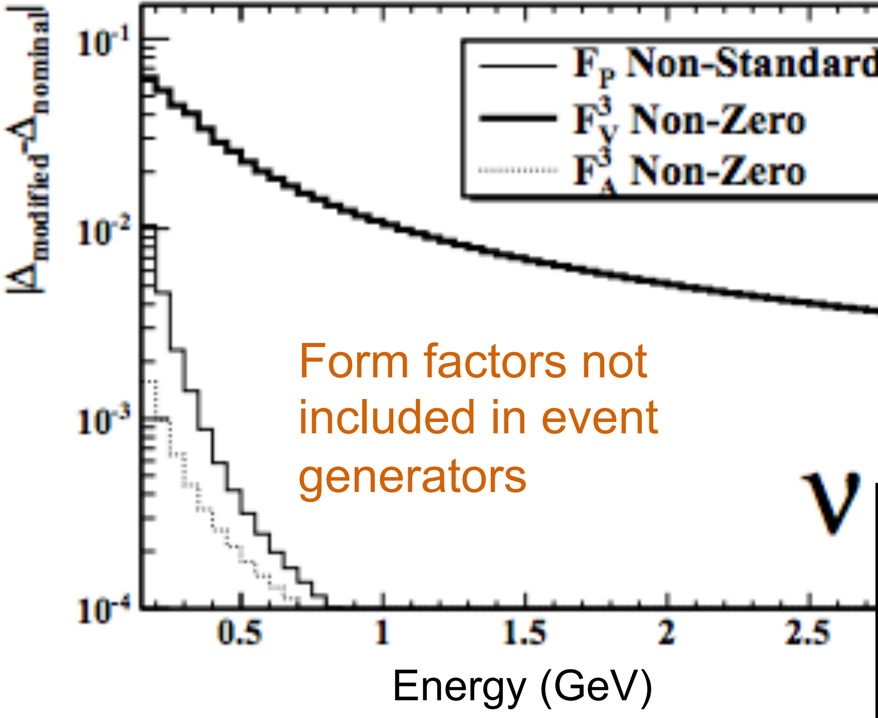
Point of discussion: Are we comfortable relying on cancellation among FD samples as a significant handle on controlling this systematic?

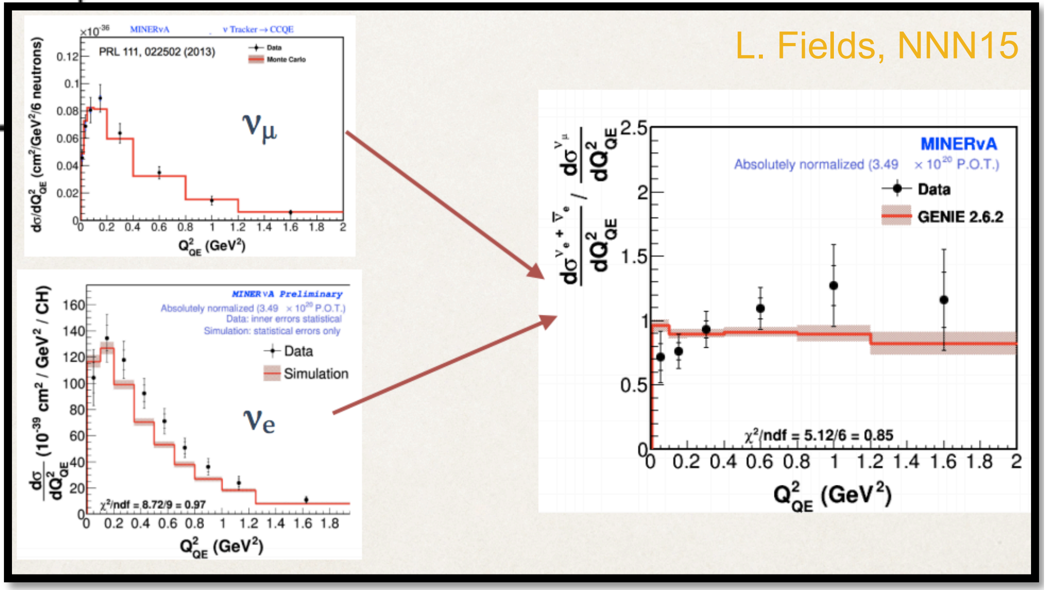
Cross-Section Ratios

arXiv:1206.6745 (Day, McFarland)



Form factors not included in event generators

MINERvA CCQE
arXiv:1509.05729



L. Fields, NNN15

Handles on (FD) 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
- Improved neutrino interaction model will reduce impact of imperfect reconstruction of neutrons and low-energy protons on analysis
- Experience from Intermediate Neutrino Program LAr TPCs expected to inform simulation, reconstruction, and calibration of DUNE's far detector
- Calibration program: LArIAT, CAPTAIN, protoDUNE
- Plan for how to combine data from test beam experiments, other neutrino experiments, in-situ data still developing
- Point of discussion: Cancellation of detector effects between ND and FD a priority? Which effects can we expect to cancel for an argon-based ND given differences in geometry, containment, space-charge effect, readout scheme, etc?

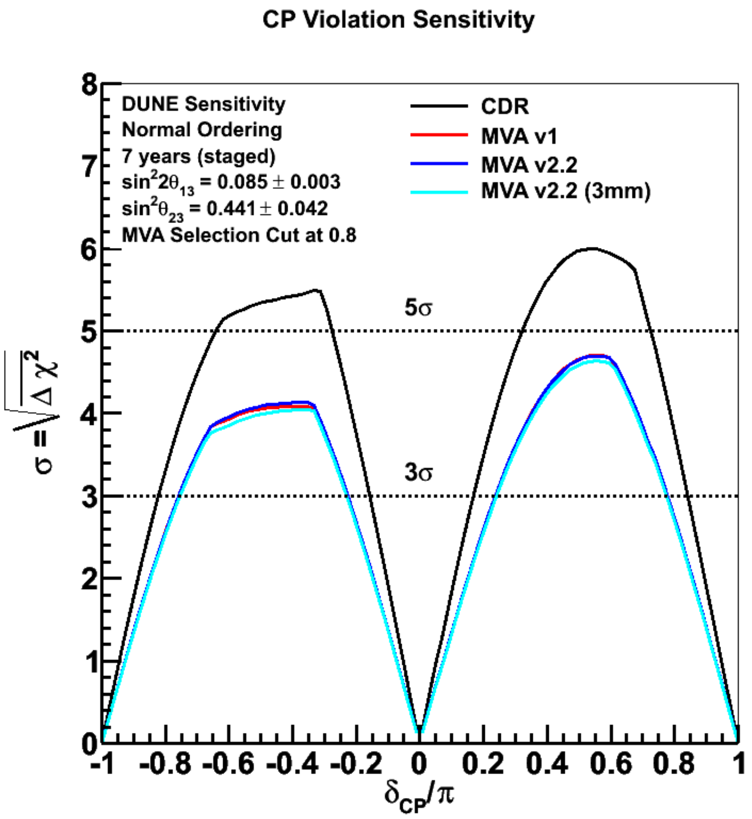
Tools to Study Systematics

- MVAtoGLoBES
- Expanded GLoBES capability
- MGT
- LOAF
- VALOR
- New developments

Primary tools used by NDTF, so you will hear a lot about these later…will leave LOAF & VALOR discussion for those talks

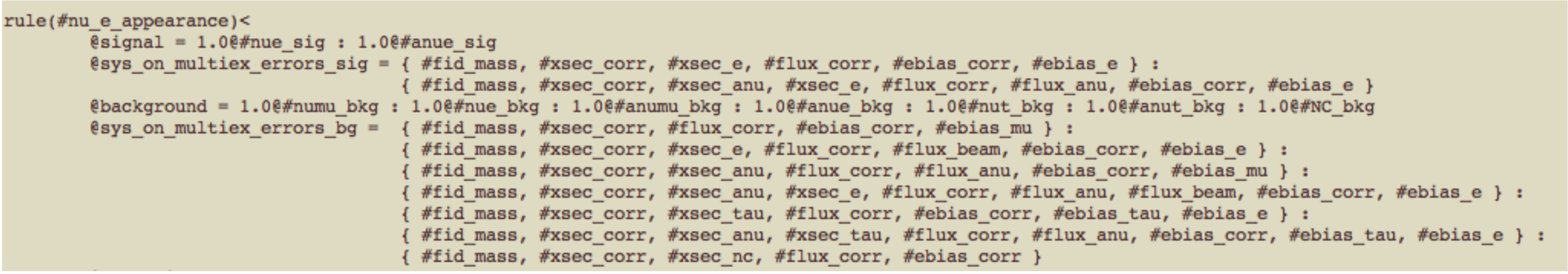
MVAtoGLoBES

- Same as CDR-era configurations, except efficiency and smearing comes from output of MVA selection (LArSoft)
- Allows MC-level systematic studies – change a parameter and see what happens to sensitivity
- Reconstruction/selection algorithms still in development, so this method may not yet be sensitive to many effects



Expanded GLoBES

- “New” version of GLoBES allows:
  - Correlated systematics
  - Multiple detectors (explicit inclusion of ND)
  - Energy dependent systematics
  - Simple energy scale uncertainty
- We have a DUNE-like configuration (from LBNE days) that includes separate normalization systematics for each component (flux, x-sec, detector) with appropriate correlations
  - Fits are slow – parallelization/optimization needed
  - Have not fully explored this configuration – opportunity for new effort!

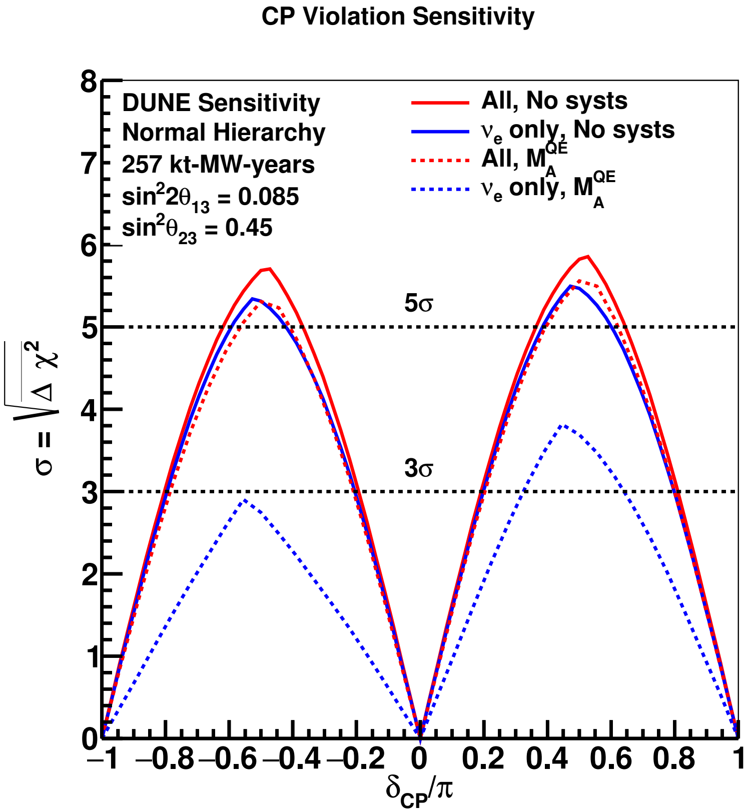


```
rule(#nu_e_appearance)<
        @signal = 1.0@#nue_sig : 1.0@#anue_sig
        @sys_on_multiex_errors_sig = { #fid_mass, #xsec_corr, #xsec_e, #flux_corr, #ebias_corr, #ebias_e } :
                                     { #fid_mass, #xsec_corr, #xsec_anu, #xsec_e, #flux_corr, #flux_anu, #ebias_corr, #ebias_e }
        @background = 1.0@#numu_bkg : 1.0@#nue_bkg : 1.0@#anumu_bkg : 1.0@#anue_bkg : 1.0@#nut_bkg : 1.0@#anut_bkg : 1.0@#NC_bkg
        @sys_on_multiex_errors_bg =  { #fid_mass, #xsec_corr, #flux_corr, #ebias_corr, #ebias_mu } :
                                     { #fid_mass, #xsec_corr, #xsec_e, #flux_corr, #flux_beam, #ebias_corr, #ebias_e } :
                                     { #fid_mass, #xsec_corr, #xsec_anu, #flux_corr, #flux_anu, #ebias_corr, #ebias_mu } :
                                     { #fid_mass, #xsec_corr, #xsec_anu, #xsec_e, #flux_corr, #flux_anu, #flux_beam, #ebias_corr, #ebias_e } :
                                     { #fid_mass, #xsec_corr, #xsec_tau, #flux_corr, #ebias_corr, #ebias_tau, #ebias_e } :
                                     { #fid_mass, #xsec_corr, #xsec_anu, #xsec_tau, #flux_corr, #flux_anu, #ebias_corr, #ebias_tau, #ebias_e } :
                                     { #fid_mass, #xsec_corr, #xsec_nc, #flux_corr, #ebias_corr }
```

MGT

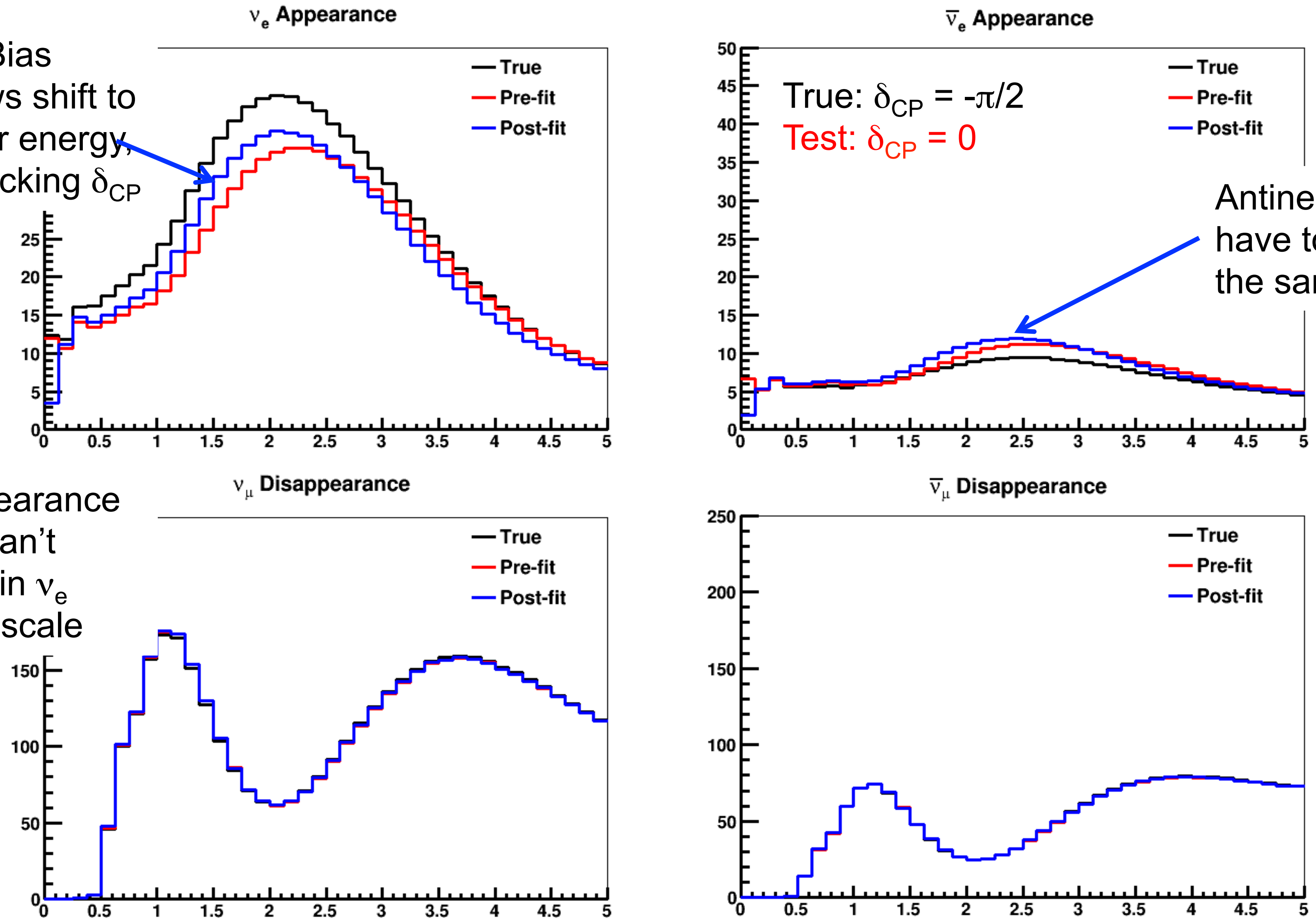
- GLoBES-based fitting package
- Performs nominal (CDR-style) GLoBES fits
- Performs fits of FD samples (Fast MC or LArSoft) including systematics parameters using GENIE-style reweights for flux and cross-section parameters and energy scale/smearing uncertainties
  - Includes uncertainty in neutrino/ antineutrino and numu/nue ratios (so perfect cancellation is not implicit)
- No ND constraints unless explicitly included as prior constraints on systematics parameters

Example: 20% variation in M_A^{QE}



Note: No ND constraint. For illustration only -- no oscillation parameter uncertainties or other systematics included.

MGT Example: Lepton Energy



LepBias allows shift to lower energy, mimicking δ_{CP}

True: $\delta_{CP} = -\pi/2$

Test: $\delta_{CP} = 0$

Antineutrinos have to shift the same way

Disappearance mode can't constrain ν_e energy scale

MGT Example: Lepton Energy

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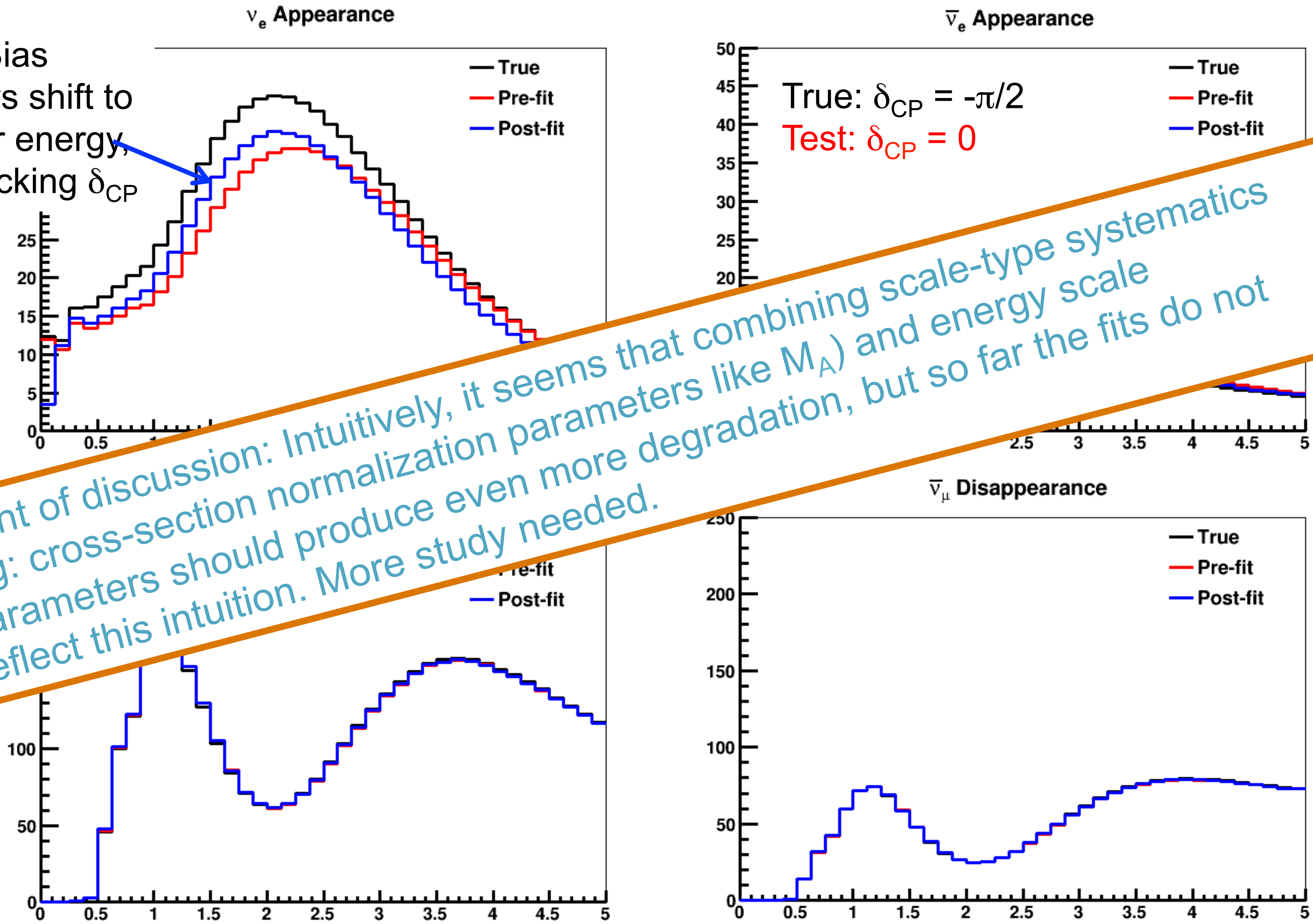

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True: $\delta_{CP} = -\pi/2$

Test: $\delta_{CP} = 0$

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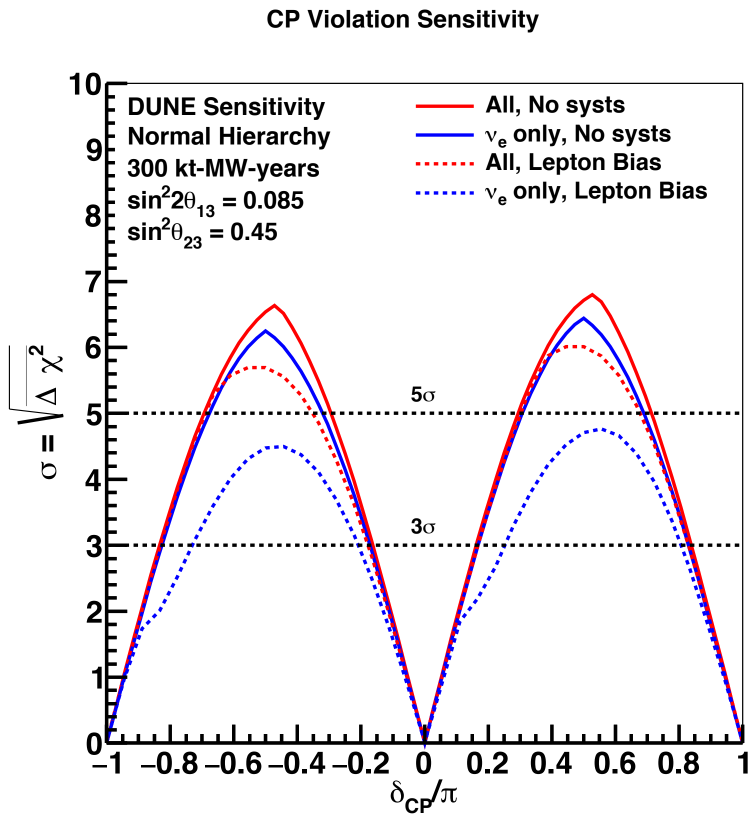
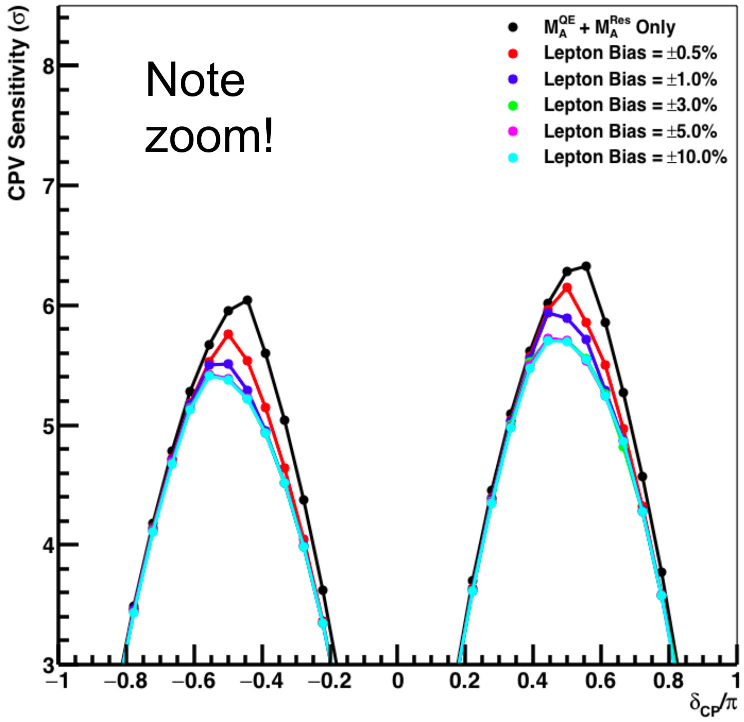
Point of discussion: Intuitively, it seems that combining scale-type systematics (eg: cross-section normalization parameters like M_A) and energy scale parameters should produce even more degradation, but so far the fits do not reflect this intuition. More study needed.

MGT Example: Lepton Energy

3% Lepton Energy Scale Uncertainty


CP Violation Sensitivity

Lepton Energy Scale Uncertainty Combined w/ M_A Uncertainty


Note zoom!

Note: No ND constraint. For illustration only -- no oscillation parameter uncertainties included.

New Developments

- VALOR joint fit to ND & FD samples
- CAFAna (NOvA fitting package)
- T. Junk fitter (based on Tevatron Higgs search)
- Stan (statistical analysis framework)
- Others?
- Please coordinate effort with the long-baseline conveners (M. Bass, D. Cherdack, M. Sanchez)

Summary of Existing Studies

- Normalization uncertainty on the appearance sample at the ~2% level or better is required (after constraints from ND and other FD samples) for CPV/precision measurements.
- Normalization uncertainty on the disappearance sample and the background level less critical.
- Preliminary studies suggest significant constraint on interaction model uncertainties from four FD samples – more quantitative study needed.
- Further study of detector effects – particularly FD energy scale uncertainty – needed. Preliminary results suggest lepton energy scale most important. Sample-sample constraints need further study.
- VALOR/LOAF results have a lot to add – see later talks
- Inputs are critical:
  - Improvements to sim/reco can/will affect these results
  - Largely dependent on GENIE reweights so far for interaction uncertainties

Ideas for Future Studies

- See Section 3.6 (Effect of Systematic Uncertainties) in physics volume of CDR. Studies suggested there include:
  - Flux covariance matrix from MINERvA ✓
  - Impact of improved models of nuclear initial state (eg: 2p2h), resonance production, FSI, etc in GENIE
  - Comparison to other generators (eg: GiBUU)
  - More quantitative understanding of sample-sample cancellation of uncertainty
  - Data-MC comparisons with test-beam and existing LArTPC detectors
- ND requirements studies:
  - Work backwards from FD – what level of constraint is required? Some attempt at this previously with mgt studies – needs to be completed and quantified. New effort also planned.

ND Physics

- See Chapter 6 (Near Detector Physics) in physics volume of CDR. ND goals are:
  1. Constrain systematics for oscillation physics
  2. Precision measurements of neutrino interactions
  3. New physics searches
- Precision measurements
  - Order 100 million neutrino interaction and 40 million antineutrino interactions in 5 years (for 7t ND)
  - QCD tests
  - $\sin^2\theta_W$
  - Isospin physics
- BSM Physics:
  - Low-mass dark matter (requires additional ND)
  - Light sterile neutrino
  - Heavy neutrinos
  - See plenary from January 2017 collaboration meeting for details (https://indico.fnal.gov/getFile.py/access?contribId=20&sessionId=3&resId=0&materialId=slides&confId=10641)

In lieu of conclusion…