“Requirements” for protoDUNE measurements to facilitate long-baseline physics analyis

Elizabeth Worcester (BNL)
protoDUNE Science Workshop
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Overview

- Long-baseline physics studies are not sufficiently advanced to establish firm requirements; my goal here is to comment on the types of measurements that affect various systematics and provide some sense of scale for the required measurements
- Intro to DUNE long-baseline systematics
- Sources of systematic uncertainty
  - Oscillation parameters
  - Flux
  - Interaction model
  - Detector
- Background rejection
- Note: Most of the work being shown has been done with the SP far detector in mind, but should be equally applicable to the DP far detector as these are largely parameterized studies not connected to a particular detector simulation

Simple Systematics Treatment for Nominal DUNE Sensitivities

- 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 ($\nu_{e,}$ $\bar{\nu}_{e,}$ $\nu_{\mu,}$ $\bar{\nu}_{\mu}$) 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.

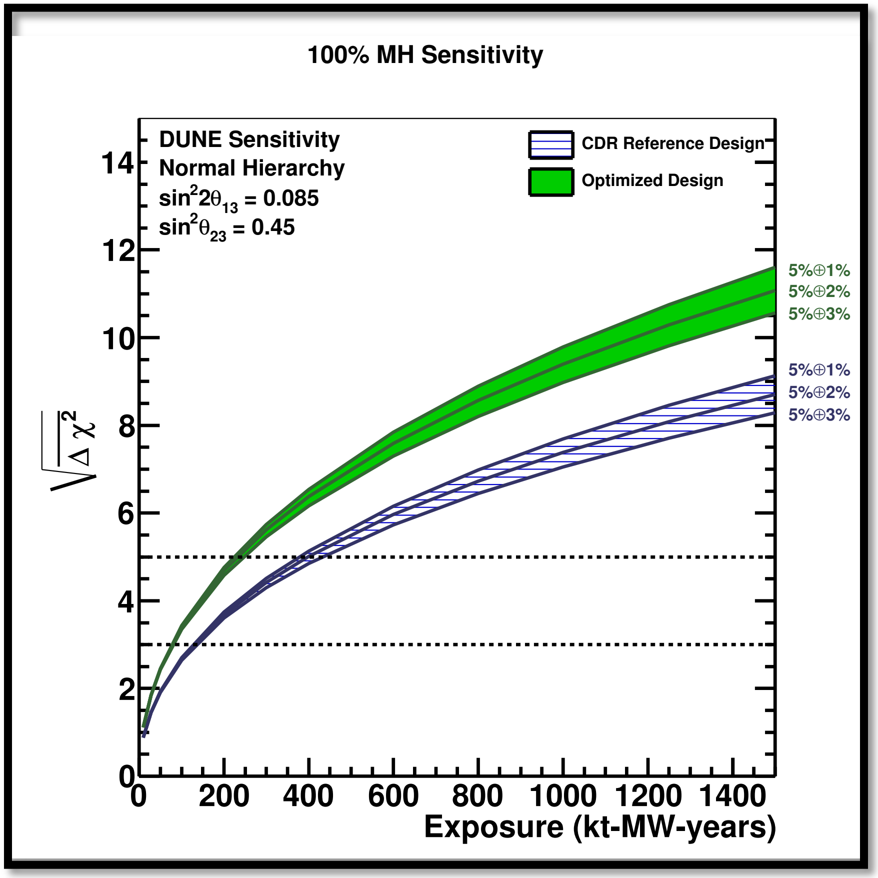
Anticipated Uncertainties

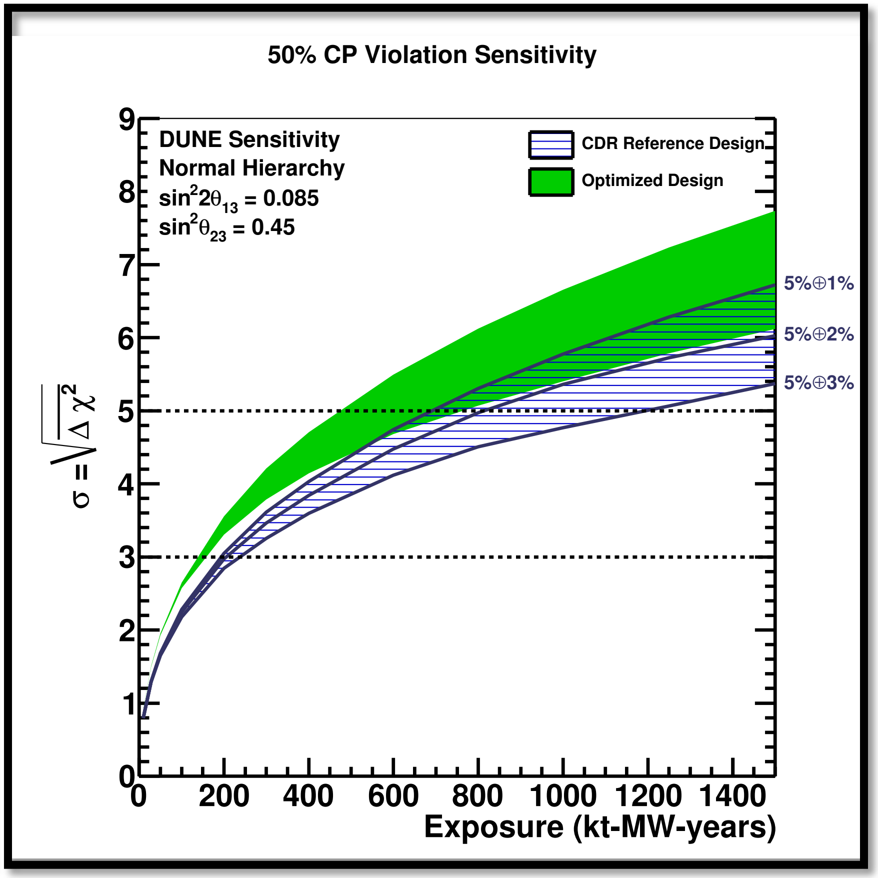
Source of Uncertainty	MINOS ν_e	T2K ν_e	Goal for DUNE ν_e
Beam Flux	0.3%	3.2%	2%
Interaction Model	2.7%	5.3%	~2%
Energy Scale (ν_μ)	3.5%	Included above	(2%) included in 5% ν_μ uncertainty
Energy Scale (ν_e)	2.7%	2.5% includes all FD effects	2%
Fiducial Volume	2.4%	1%	1%
Total Uncertainty	5.7%	6.8%	3.6%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

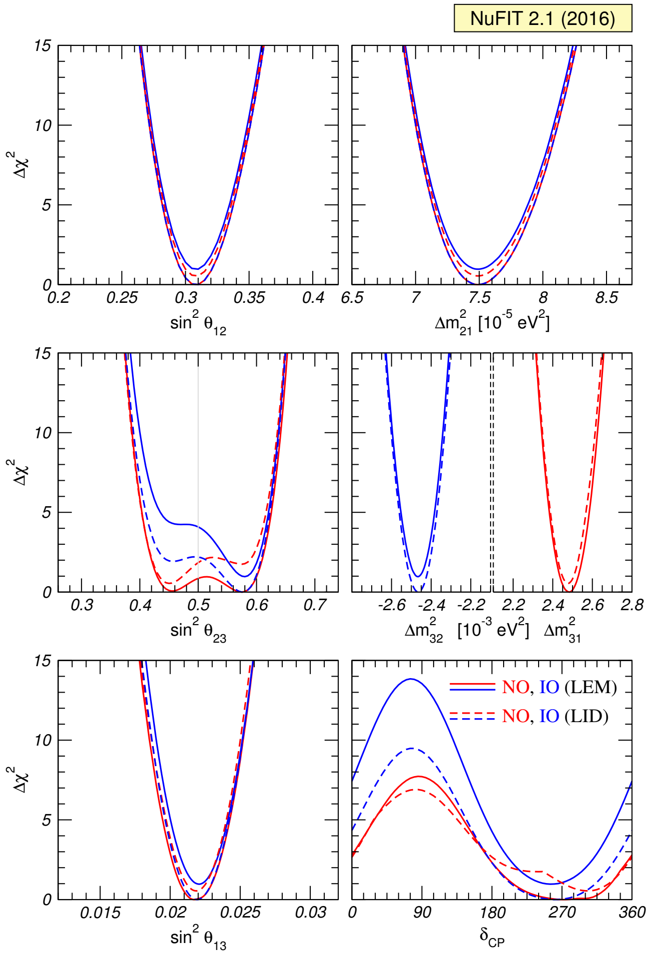
DUNE CDR:





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.

Oscillation Parameters

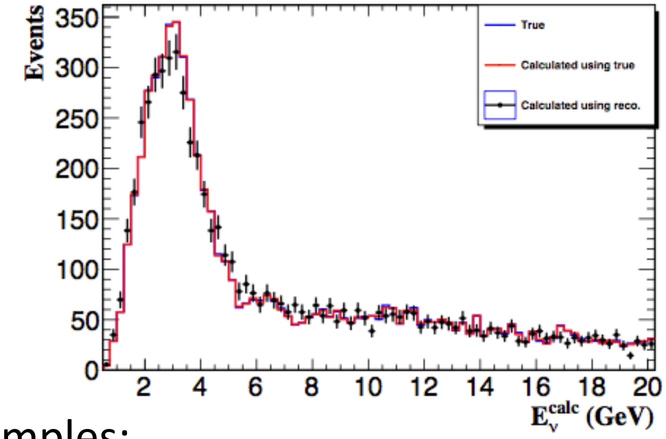


- Sensitivity calculations depend on central values and uncertainties for oscillation parameters
- θ_{13}, θ_{12}, Δm^2_{21}, Δm^2_{32} known to ~2%-2.5%
- θ_{23} known to ~6% (octant unknown)
- Nominal sensitivity studies allow oscillation parameters to vary constrained by NuFit uncertainties
- Many of the following sensitivity studies are done with oscillation parameters **fixed** to study the effect of individual other sources of uncertainty
  - So in some cases, freedom introduced by a given systematic is already present because of oscillation parameter uncertainty

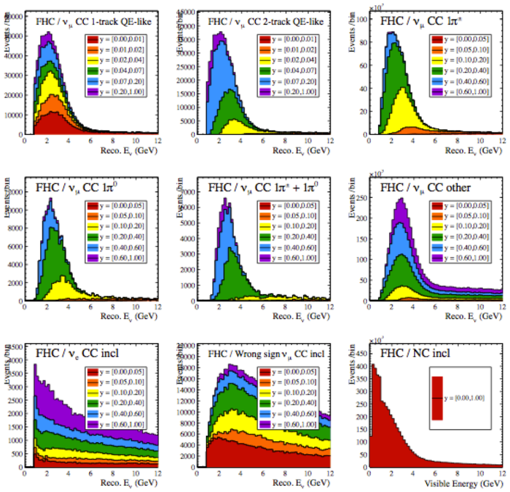
Flux

- 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%
- (Semi)-alternatively: Fit of many ND samples to constrain flux and x-section parameters (eg: VALOR)
- (Semi)-alternatively: Full fit of ND and FD samples (eg: VALOR)

Fast MC study of ν-e scattering in ND:



ND Samples:



Flux

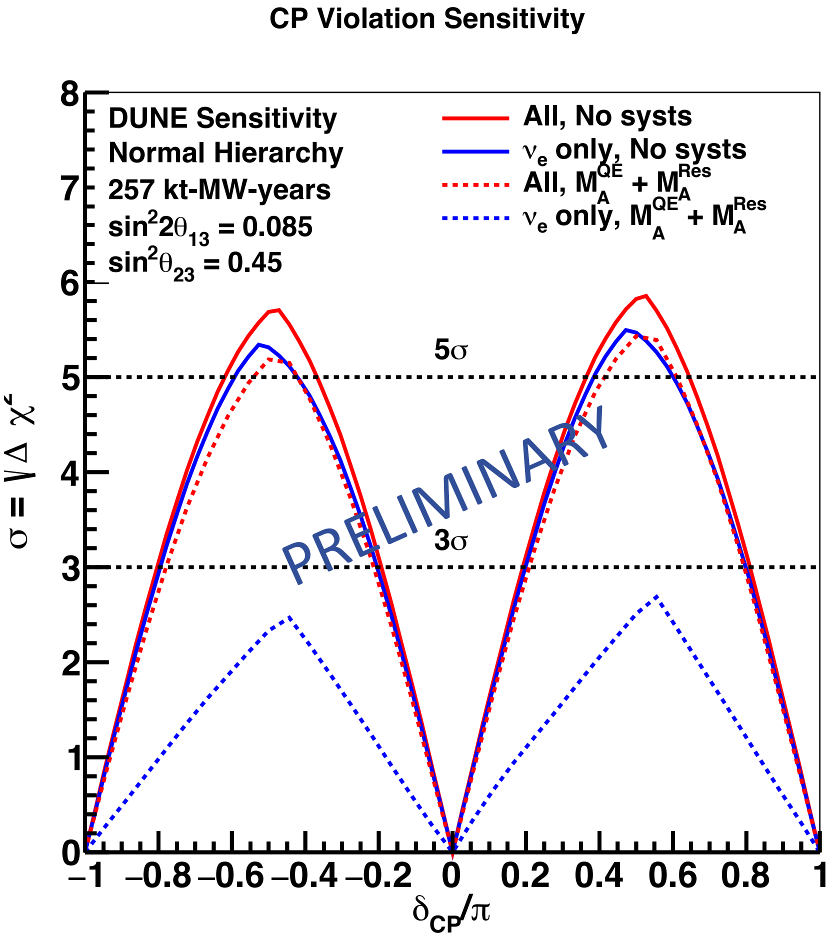
- So far, treatment somewhat uncoupled from LBL sensitivity calculations, expected to come from ND fits and/or data samples
- Low-ν_0 measurement for both ν_e and ν_μ flux, in combination with hadron production data (NA61/SHINE), constrains ND/FD flux ratio at the ~1% level
  - Requires precise knowledge of relative ν_μ energy scales in near and far detectors; for FGT ND this is expected to be ~0.2%, so relative uncertainty dominated by FD energy scale uncertainty
  - Suggests goal of "as well as we can do" – FD ν_μ energy scale will be limiting quantity for low-ν_0 ND/FD measurement
- Relevant protoDUNE measurement: muon energy scale calibration
  - Compare data & MC to known beam energy
  - Understand which detector/simulation parameters affect this measurement
  - Evaluate multiple scattering technique relative to range for contained muons
    - Robert notes this will be difficult in presence of SCE; discuss whether SCE calibration will be sufficient to overcome this

Interaction Models

- 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 $\nu/\bar{\nu}$

FD Interaction Constraints

- FastMC with **no** ND constraints
  - Vary cross-section parameters within GENIE uncertainties
    - eg: M_A^{QE} & 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



FD Interaction Constraints

- FastMC with **no** ND constraints
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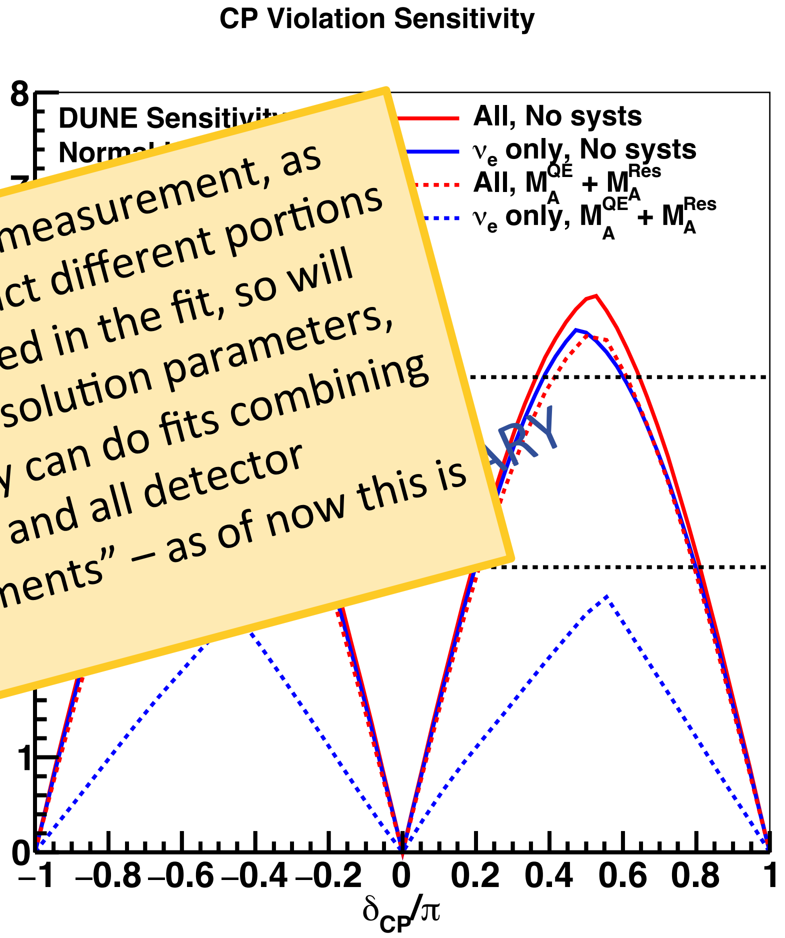


Note: This is fundamentally a spectral measurement, as different interaction parameters impact different portions of the spectra that are being compared in the fit, so will be impacted by all energy scale & resolution parameters, including missing energy. Eventually can do fits combining all interaction model uncertainties and all detector uncertainties to provide "requirements" – as of now this is simply motivation…

Detector Effects

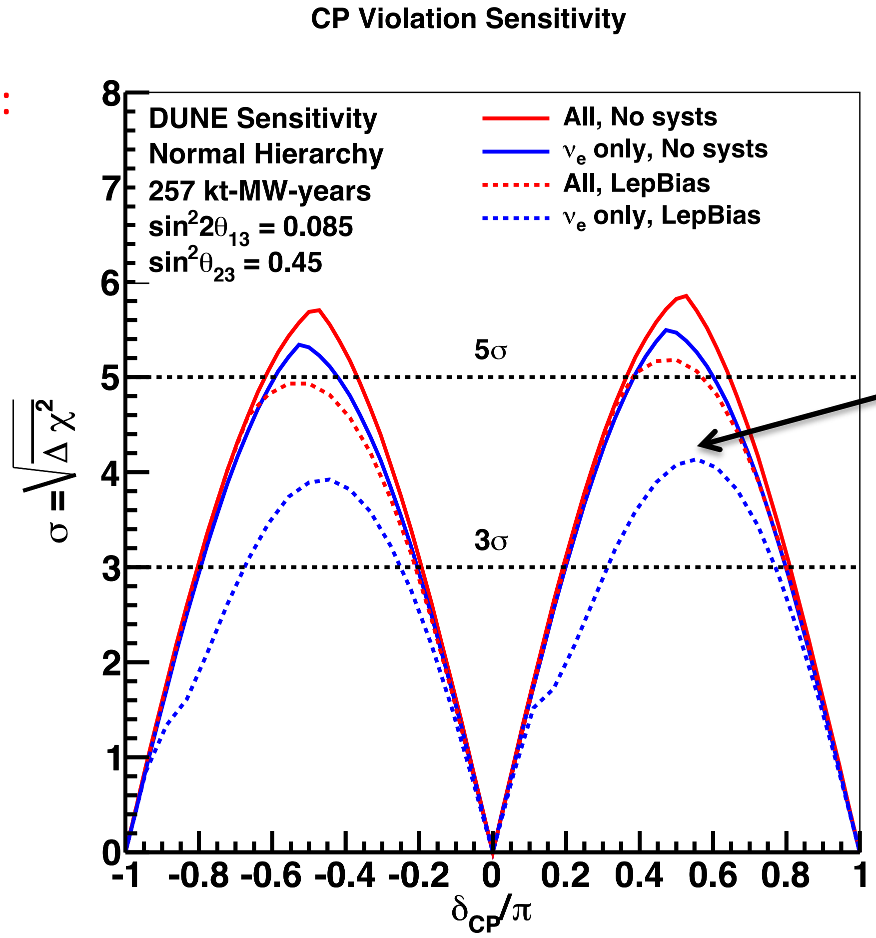
- Lepton energy resolution and energy scale uncertainty
  - Electrons and muons uncorrelated; understand particle/antiparticle differences
  - Nonlinearity
- Hadronic energy resolution and energy scale uncertainty
  - Will have different contributions from different particles types (protons, neutrons, charged pions, neutral pions) in different portions of the neutrino spectrum
  - Includes effects of undetected energy
  - Nonlinearity
  - Understand correlation between ν_e/ν_μ and $\nu/\bar{\nu}$
- Position resolution/uncertainty
  - Affects ability to calibrate position dependent effects
  - Affects fiducial mass uncertainty
  - Affected by SCE position distortion
- Position-dependent energy & position effects
  - Space charge effect
  - Other sources of non-uniformity
- Time-dependent energy and position effects
  - Demonstrate space charge effect is ~static (?)
  - Other sources of time dependence

Energy Systematic Studies

- LepSmear
  - Implemented as fractional change in lepton resolution
  - 1σ = 2.5%, 5%, 10%, 20%
  - $f_{\nu\mu}$= 1, $f_{\nu/\bar{\nu}}$= $1\sigma \oplus 1\sigma$, $f_{\nu e/\nu\mu}$= 100, $f_{\nu\tau/\nu\mu}$= 100
- LepBias
  - Implemented as simple nonlinearity: $(1 + \sigma) * E_{\text{lepton}}$
  - 1σ = 1%, 3%, 5%, 10%
  - $f_{\nu\mu}$= 1, $f_{\nu/\bar{\nu}}$= $1\sigma \oplus 1\sigma$, $f_{\nu e/\nu\mu}$= 100, $f_{\nu\tau/\nu\mu}$= 100
- HadSmear
  - Implemented as fractional change in resolution of hadron system
  - 1σ = 2.5%
  - $f_{\nu\mu}$= 1, $f_{\nu/\bar{\nu}}$= 100, $f_{\nu e/\nu\mu}$= 0.025, $f_{\nu\tau/\nu\mu}$= 0.1
- HadBias
  - Implemented as simple nonlinearity: $(1 + \sigma) * E_{\text{hadron-system}}$
  - 1σ = 1%, 3%, 5%, 10%
  - $f_{\nu\mu}$= 1, $f_{\nu/\bar{\nu}}$= 100, $f_{\nu e/\nu\mu}$= $1\sigma \oplus 1\sigma$, $f_{\nu\tau/\nu\mu}$= 0.1
- NeutronBias (previously "HadBias")
  - Implemented as variation in fraction of neutron energy observed
  - 1σ = 20%
  - $f_{\nu\mu}$= 1, $f_{\nu/\bar{\nu}}$= 100, $f_{\nu e/\nu\mu}$= 0.025, $f_{\nu\tau/\nu\mu}$= 0.1

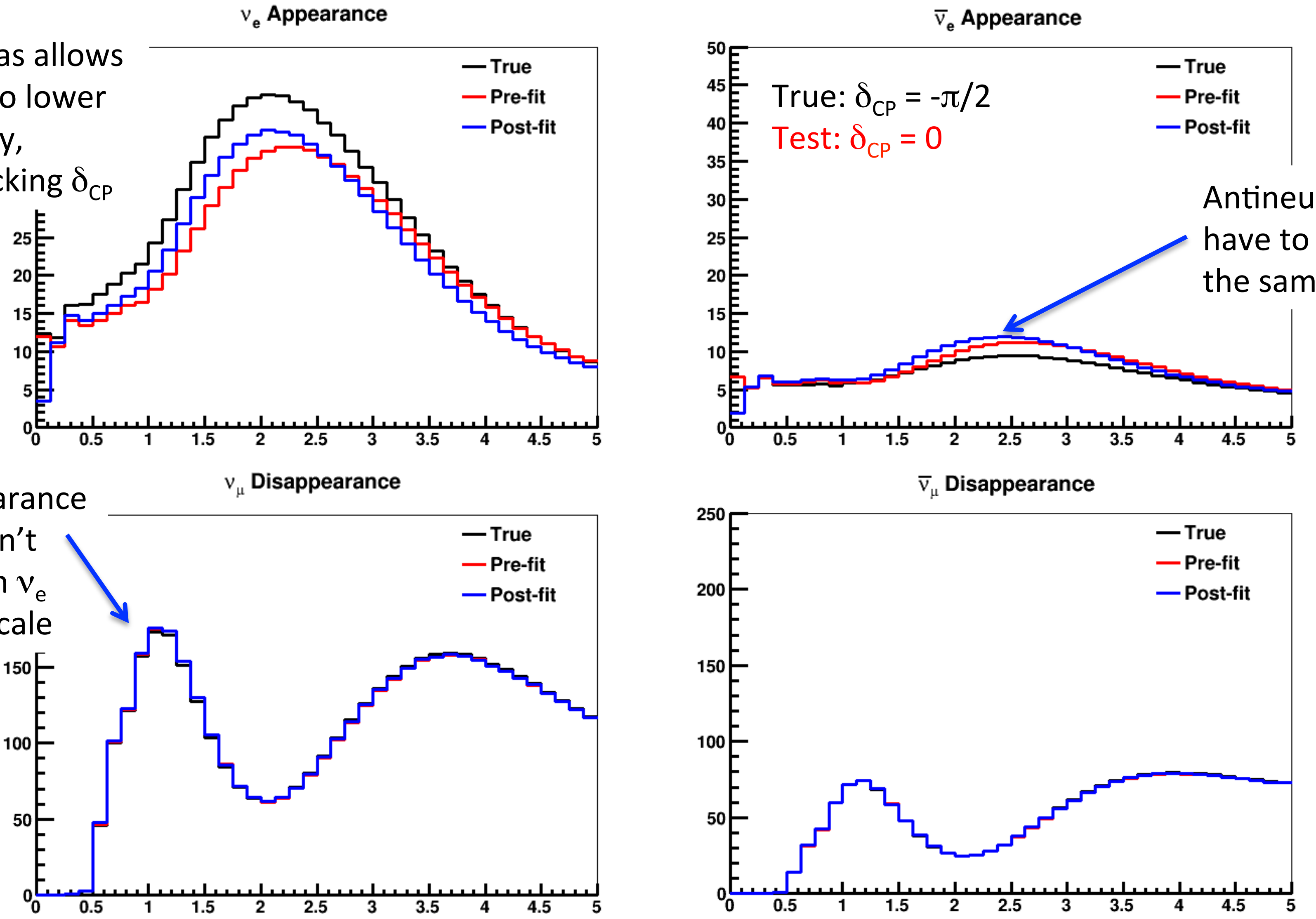
Sample CPV Sensitivity Fit: LepBias

Previous study with different assumptions: not for direct comparison with current results



ν_e only fit has serious degradation: we rely on the constraint from antineutrinos in the 4-sample fit

Sample CPV Sensitivity Fit: LepBias



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

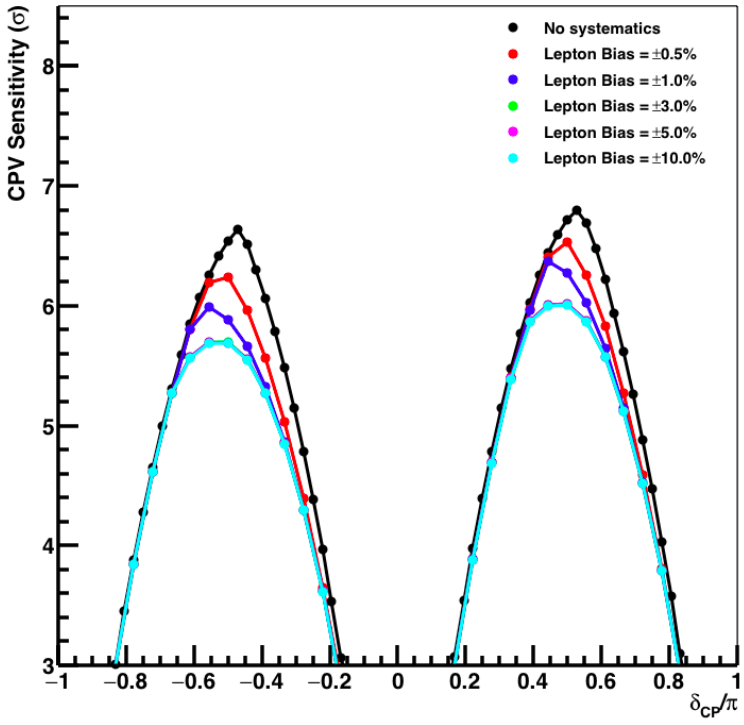
True: $\delta_{CP} = -\pi/2$

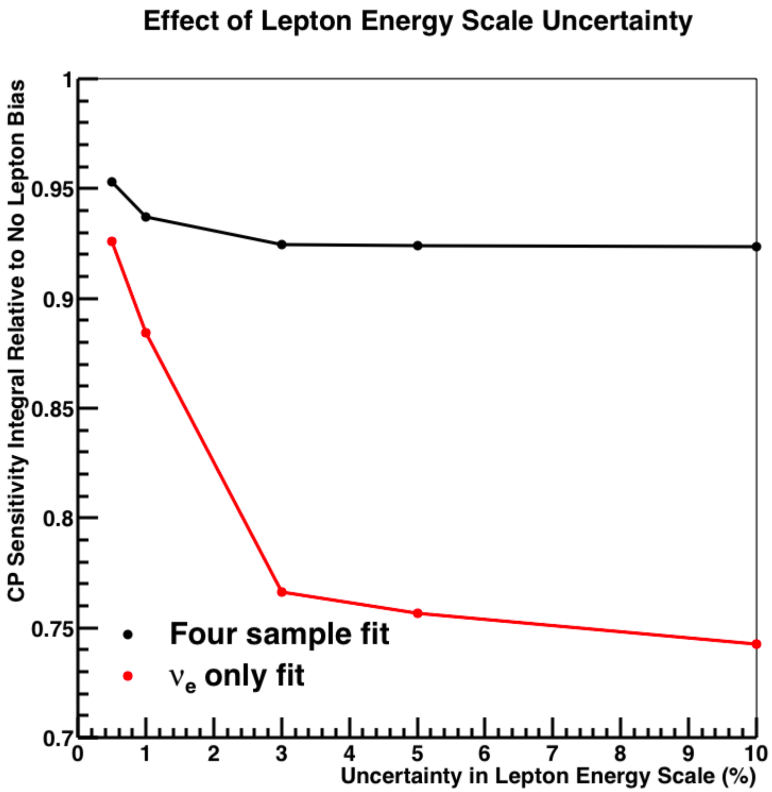
Test: $\delta_{CP} = 0$

Antineutrinos have to shift the same way

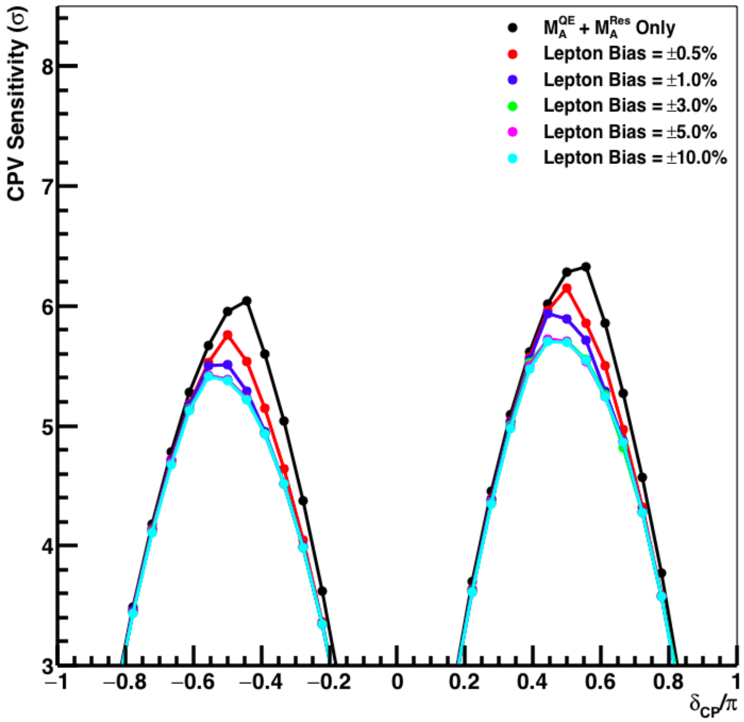
Disappearance mode can't constrain ν_e energy scale

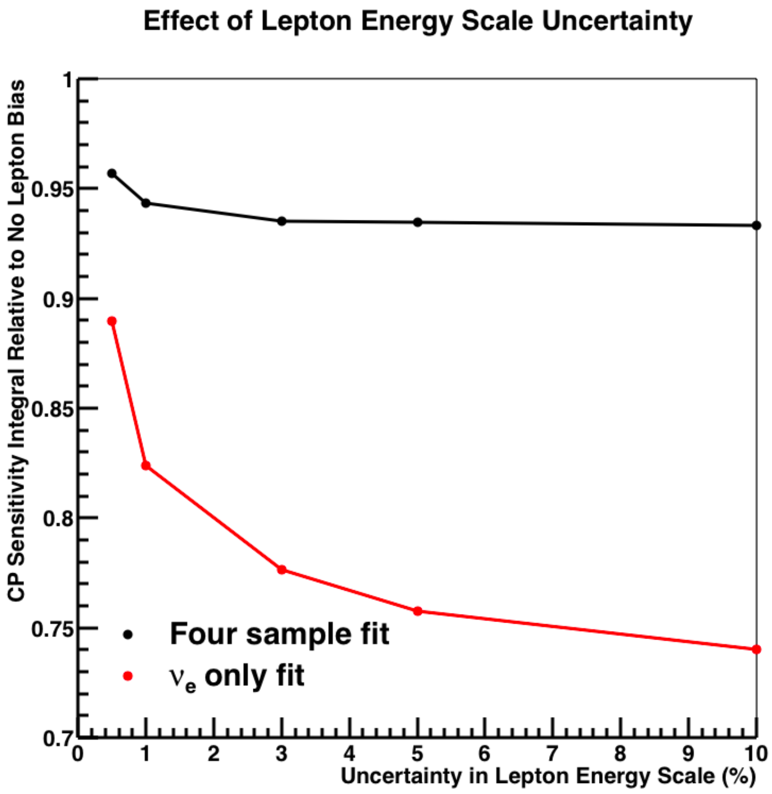
Lepton Bias


CPV Sensitivity (σ)
3
4
5
6
7
8
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
δ_{CP}/π
● No systematics
● Lepton Bias = ±0.5%
● Lepton Bias = ±1.0%
● Lepton Bias = ±3.0%
● Lepton Bias = ±5.0%
● Lepton Bias = ±10.0%

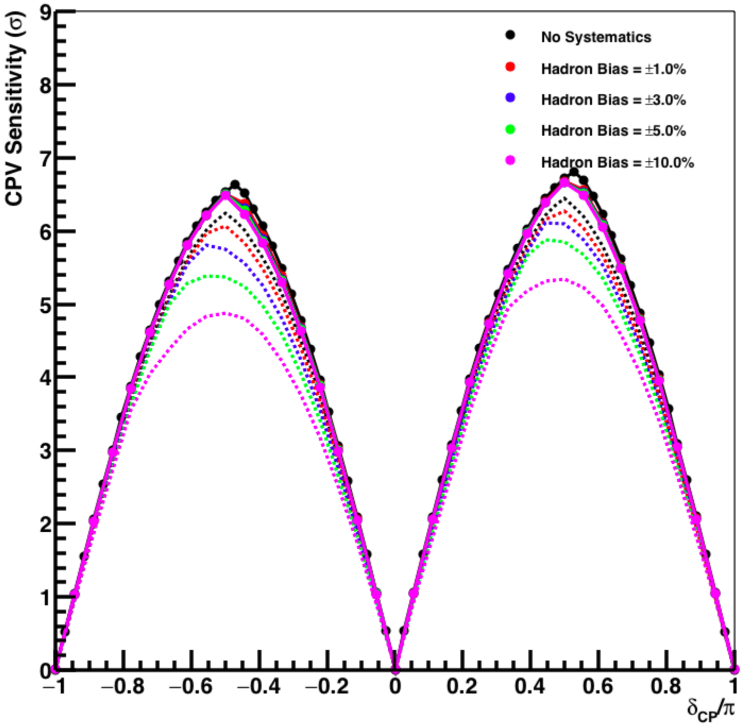

Effect of Lepton Energy Scale Uncertainty
CP Sensitivity Integral Relative to No Lepton Bias
0.7
0.75
0.8
0.85
0.9
0.95
1
0
1
2
3
4
5
6
7
8
9
10
Uncertainty in Lepton Energy Scale (%)
● Four sample fit
● ν_e only fit

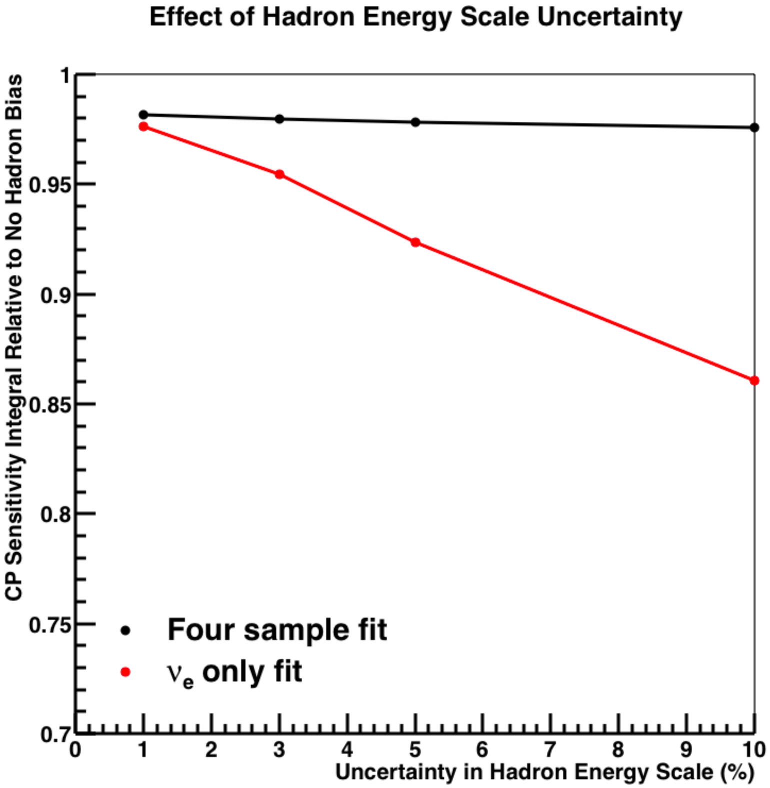
Cross-section + Lepton Bias





Hadron Bias

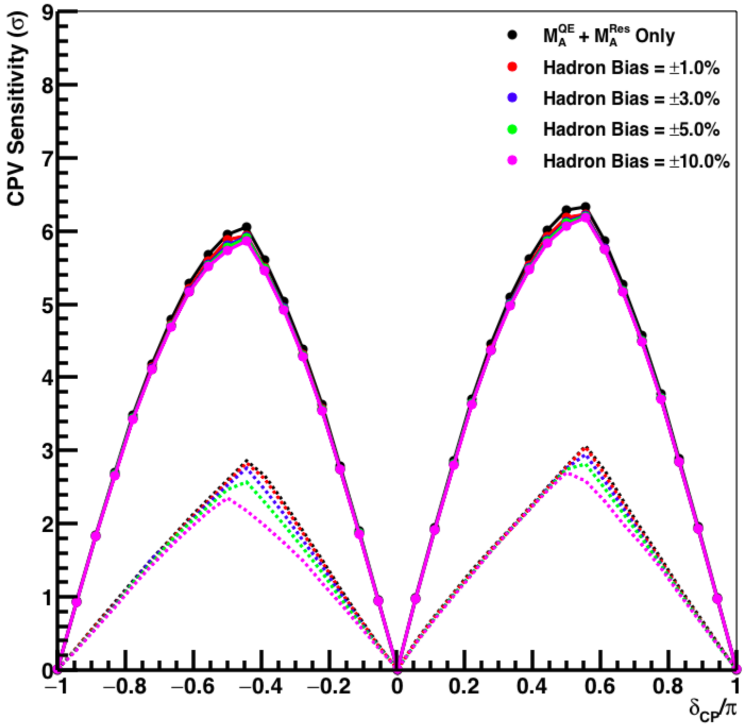




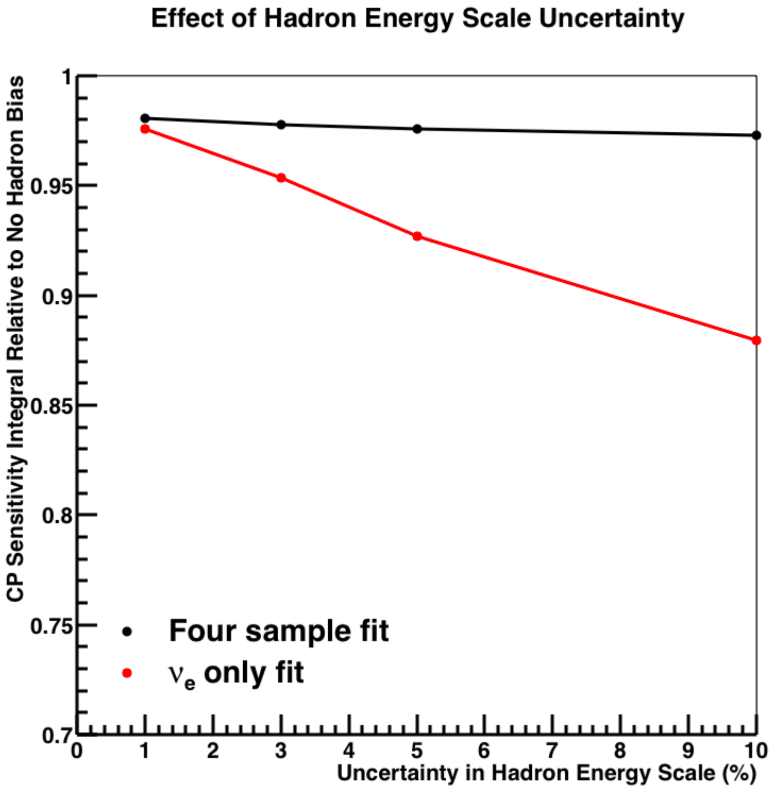
Solid = 4 sample

Dashed = ν_e only

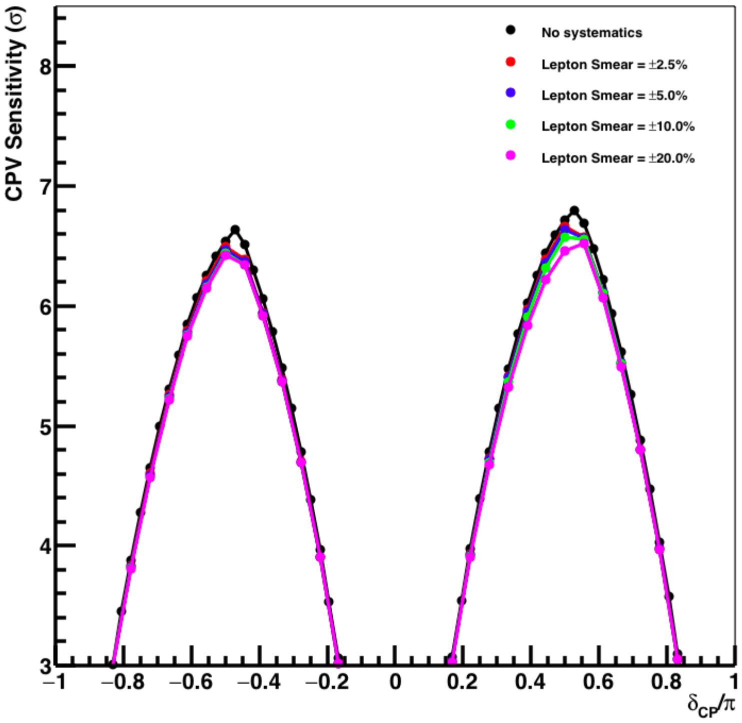
Cross-Section + Hadron Bias

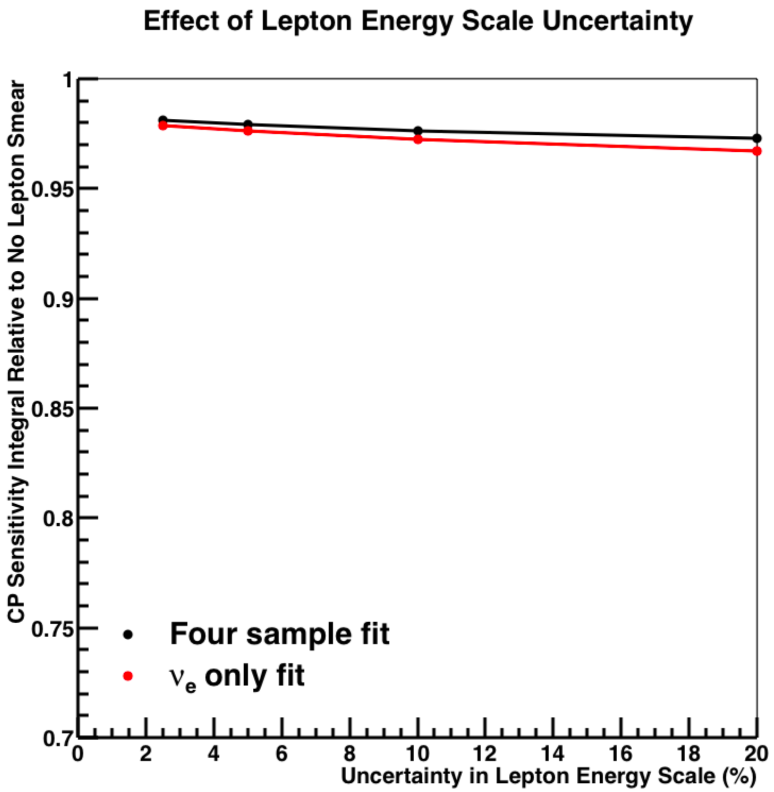


Effect of Hadron Energy Scale Uncertainty



Lepton Smearing

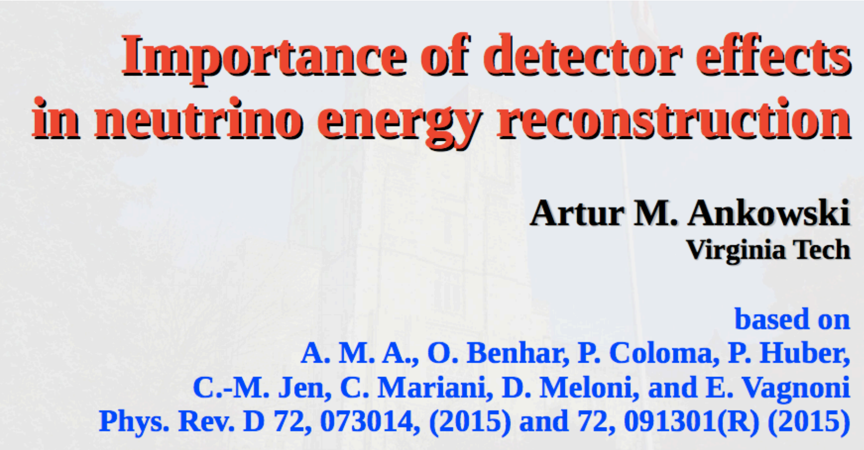




Notes on this study:

- So far, energy scale uncertainty more troublesome than resolution uncertainty
  - LepBias only effect showing significant degradation in CPV sensitivity; even here, with existing correlation assumptions, need better than 3% calibration to impact CPV sensitivity
- Effect of sample-sample correlations
  - Cancellation of uncertainty dependent on assumptions about sample-sample correlations
  - More thought/feedback needed to understand appropriate values for these
  - Demonstration of these correlations (via measurements) would be extremely useful
  - Without significant sample-sample correlations, any energy scale uncertainty has vey negative impact on CPV sensitivity
- Interplay with other systematics
  - Studies done with oscillation parameters fixed to isolate effect; ultimately need to vary simultaneously
  - Somewhat surprising that combination with cross-section parameters not more troublesome…more study needed
- Existing machinery to study detector effects somewhat unwieldy; systematic effects will eventually be built in to LArSoft and/or LOAF fitter to better facilitate this kind of study

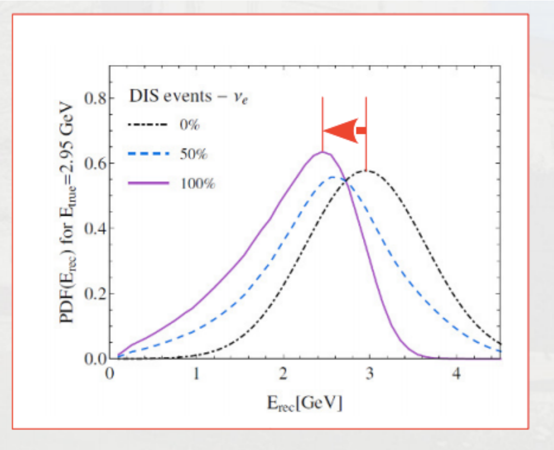
Effect of Missing Energy



Importance of detector effects in neutrino energy reconstruction

Artur M. Ankowski
Virginia Tech

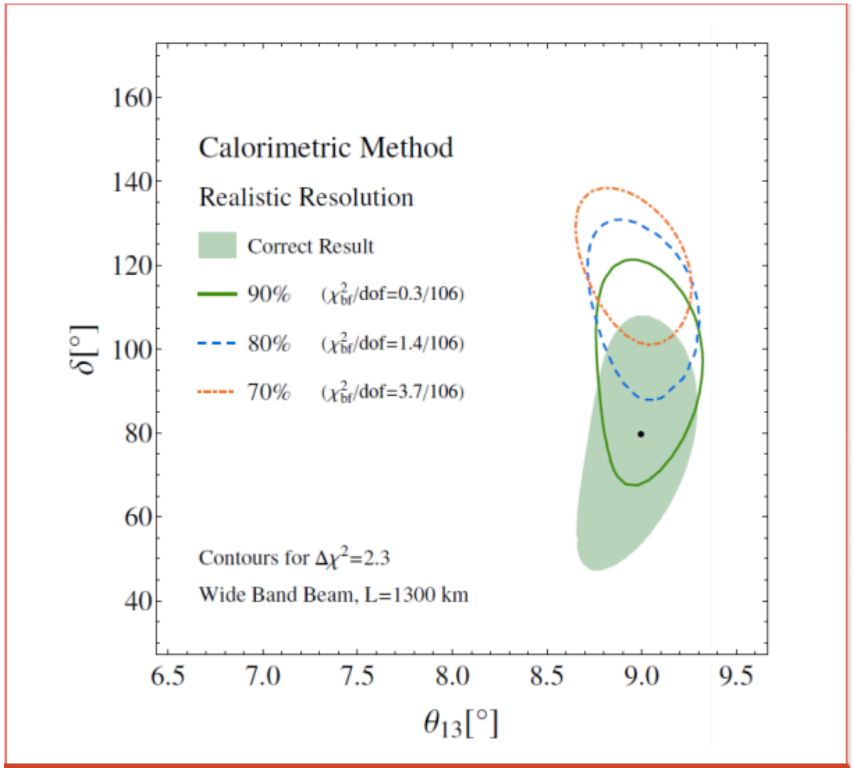
based on
A. M. A., O. Benhar, P. Coloma, P. Huber,
C.-M. Jen, C. Mariani, D. Meloni, and E. Vagnoni
Phys. Rev. D 72, 073014, (2015) and 72, 091301(R) (2015)



- Consider separate efficiency to detect individual particle types; reconstruct neutrino energy calorimetrically
  - 80% for leptons, charged pions, kaons, gammas
  - 60% for neutral pions
  - 50% for protons
  - 0% for neutrons
- With thresholds of 0 MeV for leptons and EM particles, 20 MeV for pions and kaons, 40 MeV for protons
- Manually adjust amount of missing energy accounted for in analysis to see impact on physics measurements

Effect of Missing Energy

A. Ankowski



The missing energy needs to be estimated with a ~20% accuracy or better

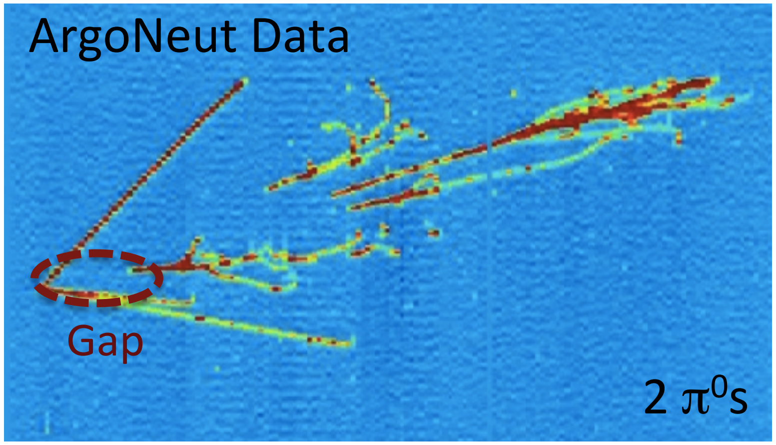
- Similar effects included in Fast MC studies
- In both this study and Fast MC, thresholds and efficiencies are educated guesses
- (Some) particle ID algorithms and efficiencies can be studied in protoDUNE
  - Ideally as f(E)

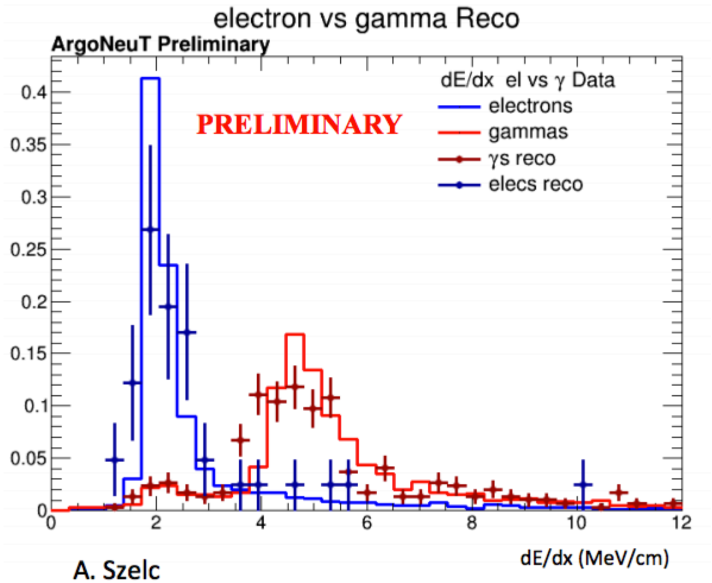
protoDUNE Measurements for Detector Effects

- EM energy scale & resolution
  - e beam
  - $\pi^0 \rightarrow \gamma\gamma$ from charge exchange π^0s
  - Differences between e and γ ?
- Muon energy scale & resolution: μ beam
- Hadronic energy scale & resolution: π^+, p beam
- Position resolution & uncertainty: beam particles, cosmic muons with known CRT positions ?
- Detector uniformity: cosmic muons
- Time dependent effects: all
- All require development of particle ID/reconstruction algorithms, identification/removal of cosmic tracks, calibration of detector including space charge effect, analysis of beamline data to determine "true" particle type and energy
- In all cases, focus on validation of simulation and analysis techniques and understanding of which detector parameters effect the measurement

Background Rejection

- Electron vs. γ particle ID for NC BG rejection
  - Gap between vertex and start of γ shower
  - dE/dx for start of showers
- Transverse momentum also provides rejection of NC interactions
- Crowded neutrino vertex or reconstruction degeneracies can degrade background rejection
- Fast MC assumes efficiency based on uBooNE MC (several years old; different detector parameters)
  - Total NC BG efficiency < 1% for >80% ν_e CC signal efficiency
- So far, DUNE MC studies have not reached required level of rejection
  - Thought to be a reconstruction issue
- In protoDUNE:
  - Demonstrate algorithm efficiency with DUNE-like detector
  - Compare to MC and understand effect of variations in detector parameters
  - Study complicated vertices (?)





A. Szelc

Summary

- protoDUNE measurements can contribute a lot to the long-baseline physics analysis
- Particularly interesting:
  - Energy scale measurements at single particle level
  - Efficiencies for calorimetry
  - Background rejection (e-γ separation)
- protoDUNE detector calibration including effective removal of space charge effects and effective removal of cosmic tracks required for these measurements
- Goal of the measurements program (from a DUNE LBL physics perspective) should be to develop and demonstrate effectiveness of measurement techniques, determination of which detector simulation parameters impact these measurements, validation of detector simulations so that these techniques may be applied in the (very different) DUNE FD environment
  - This approach is also more interesting to the LArTPC community at large and is therefore more likely to produce useful detector physics papers