Energy Systematics Studies

Elizabeth Worcester (BNL)

March 15, 2016

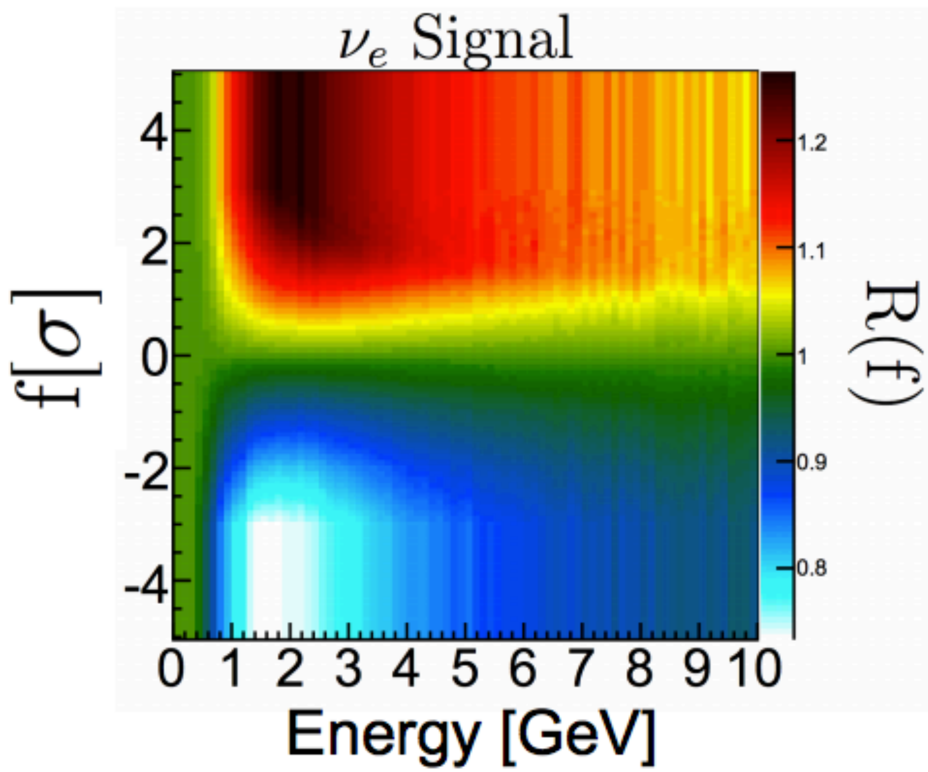
Redux of talks given at previous DUNE collaboration meetings, summarizing the methods and results for detector systematics studies.

Introduction

- Introduction to method
  - M. Bass, DocDB 9872
- Parameter variations under consideration
  - Suggestions for additional studies welcome
- Results to date

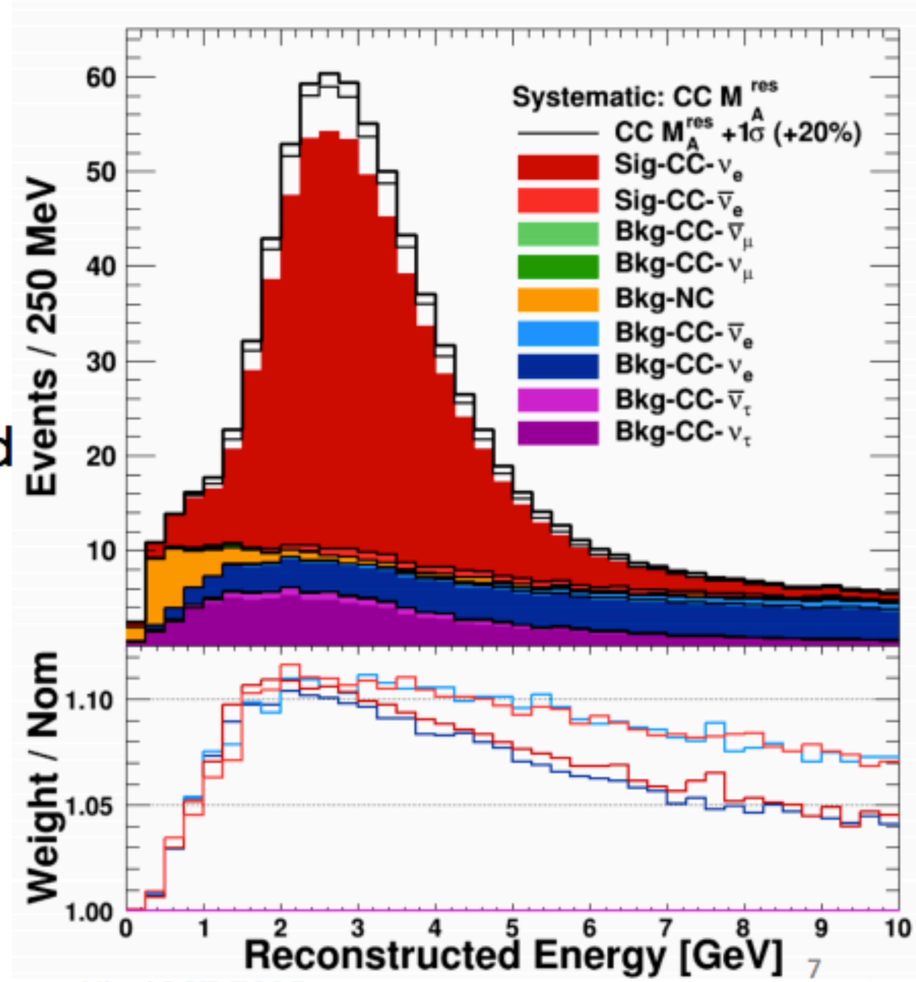
Response Functions

- Variations in event spectra from uncertainties are encoded into **response functions** that **reweight** the spectra
  - Set of nine RFs for each systematic parameter to reweight each channel contributing to signal and background
  - Right: one response function for ν_e signal channel in the LBNE ν_e appearance sample
    - CC M_A^{RES}



LBNE Systematic Example

- Example: Resonant charged-current quasi-elastic axial mass
  - $CC\ M_A^{RES}$
  - Dominant process for LBNE energies
- ν_e appearance spectrum and variations produced in each channel
- Large effects in a critical region
  - 1σ shift changes predicted event rate by 10%



arXiv:1307.7335

Response Function Event Rates

- Compute event rate in reconstructed energy bin i for channel c

$$n_{i,c}(\boldsymbol{\theta}, f) = \sum_{j}^{N_{E_{true}}} \left(R_j^c(f) \cdot P_j^c(\boldsymbol{\theta}) \cdot n_j^c \cdot S_{ij}^c \right)$$

  - n^c: Fast MC's prediction for the event rate at the FD in E_{true} bin j
  - $P^c(\boldsymbol{\theta})$: GLoBES oscillation probability for $\boldsymbol{\theta}$ set of parameters
  - S_{ij}^c: Fast MC smearing matrix ($E_{true} \rightarrow E_{reco}$)
  - $R_j^c(f)$: Fast MC systematic response function at nuisance parameter value f

M. Bass

Response Function Event Rates per Channel

- Event rates are computed separately for each channel and combined to form a signal + background
  - 4 nuisance parameters to represent theoretical uncertainties between samples
    - f_{ν_μ}, $f_{\bar{\nu}/\nu}$, f_{ν_e/ν_μ}, f_{ν_τ/ν_μ}
  - 8 nuisance parameters to represent statistical uncertainty from statistical limitations in measurement of ν_μ flux (within the Asimov data set framework)
    - $f^{stat}_{\bar{\nu}_\mu/\nu_\mu}$, $f^{stat}_{\nu_e/\nu_\mu}$, $f^{stat}_{\bar{\nu}_e/\nu_\mu}$, f^{stat}_{NC/ν_μ}, $f^{stat}_{\nu_e^{osc}/\nu_\mu}$, $f^{stat}_{\bar{\nu}_e^{osc}/\nu_\mu}$, $f^{stat}_{\nu_\tau/\nu_\mu}$, $f^{stat}_{\bar{\nu}_\tau/\nu_\mu}$

Putting it all together: log-likelihood

- All the channels are summed together to give an expected signal+background at a particular set of oscillation and nuisance parameters
- Compare true hypothesis (H0) against test hypothesis (H1)
  - e.g. $H0(\delta_{CP} = 0)$ vs $H1(\delta_{CP} = \pi/2)$
- A log-likelihood ratio is computed to test the hypothesis H1 against H0

$$\mathcal{L} = -2\ln\frac{L(\mathbf{n}^{true}|\mathbf{n}^{test'})}{L(\mathbf{n}^{true}|\mathbf{n}^{test''})} = 2\cdot\sum_{i}^{N_{reco}}\left(n_i^{true}\cdot\ln\frac{n_i^{true}}{n_i^{test'}} + n_i^{test'} - n_i^{true}\right) + \frac{f_{\nu_\mu}^2}{\sigma_{\nu_\mu}^2} + \frac{f_{\bar{\nu}/\nu}^2}{\sigma_{\bar{\nu}/\nu}^2} + \frac{f_{\nu_e/\nu_\mu}^2}{\sigma_{\nu_e/\nu_\mu}^2} + \frac{f_{\nu_\tau/\nu_\mu}^2}{\sigma_{\nu_\tau/\nu_\mu}^2} + \sum_{j=1}^{8}\frac{f_i^2}{\sigma_i^2}$$

(for one systematic)

Response Function For Energy Systematics

- Depend on reconstructed energy
  - "Regular" response functions depend only on true energy
- Energy response function is an additional smearing matrix that takes E_{reco} to E_{final}
  - "Regular" response function is a weight in true energy bins

Response Function Event Rates

- “Regular” response functions:

$$n_i(\theta, f) = \sum_{j}^{NEtrue} R_j(f) \cdot P_j(\theta) \cdot n_j \cdot S_{ij}$$

- Energy response functions (new):

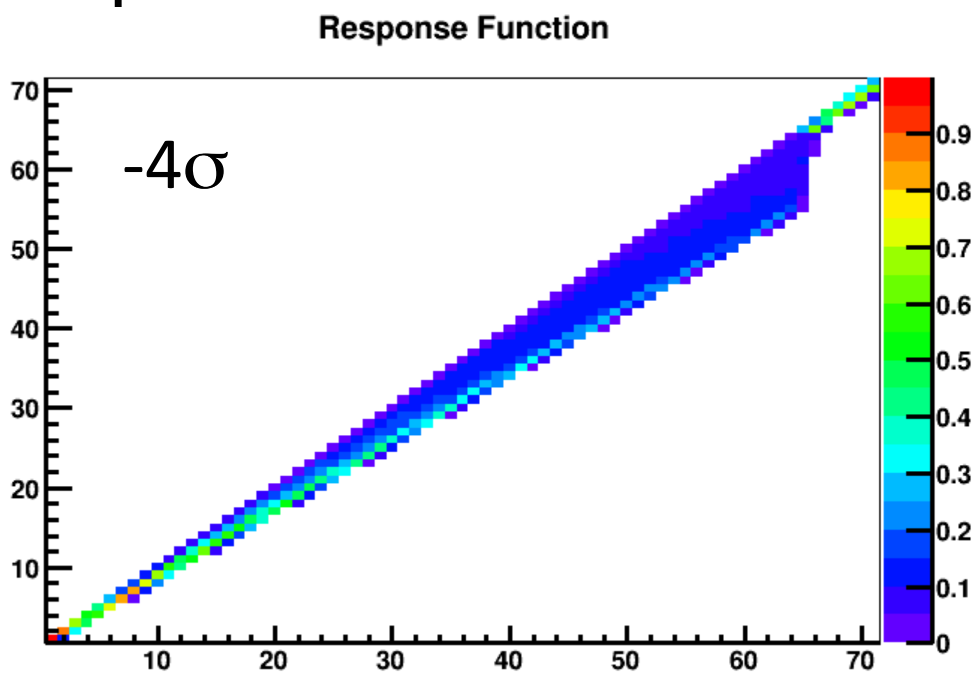
$$n_i(\theta, f) = \sum_{j}^{NEtrue} P_j(\theta) \cdot n_j \cdot \sum_{k}^{NEreco} R_{ik}(f) \cdot S_{kj}$$

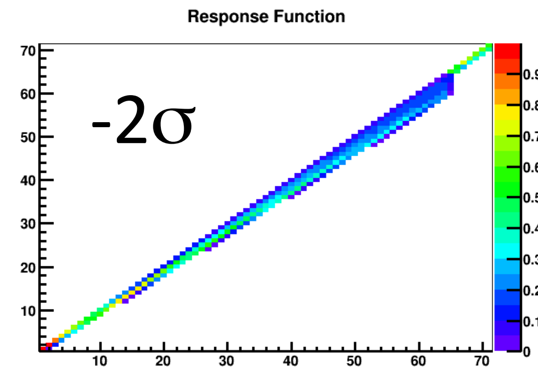
Note: This works for single energy systematics alone or in combination with “regular” response functions. Because matrix multiplication does not commute, does not mathematically work for combinations. Tests show minimal differences when considering different ordering of combinations.

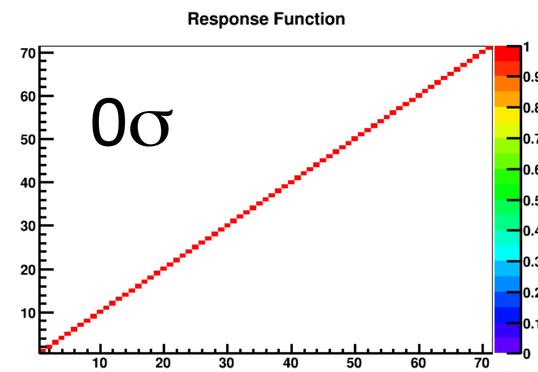
$$S'_{ij}$$

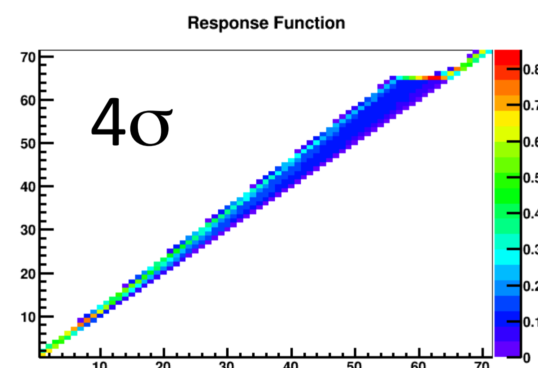
Example: LepBias

- $E_{lepton} \Rightarrow (1 + \sigma) * E_{lepton}$
- σ = 3% (a choice)
- Response matrices:









Systematics Considered

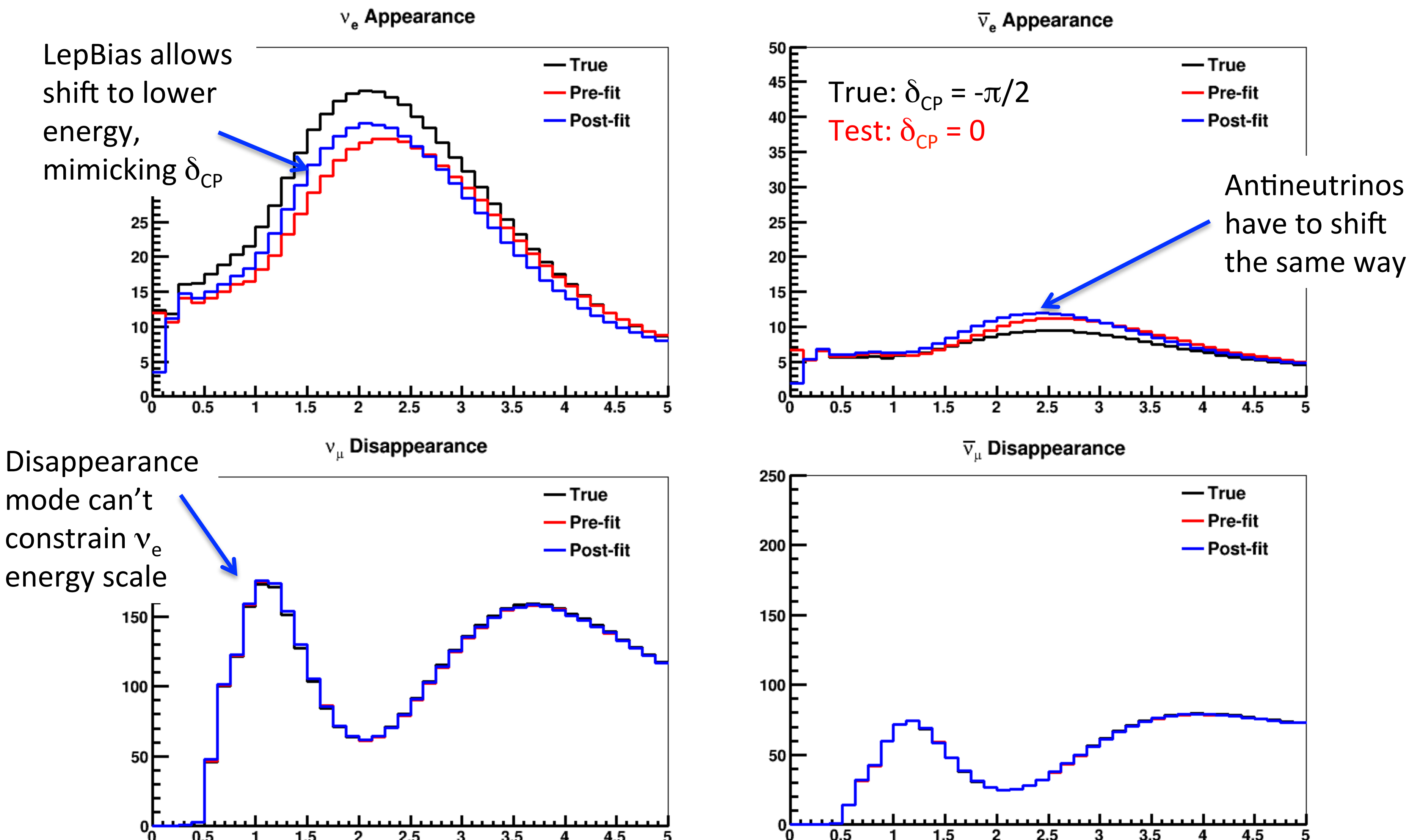
- LepSmear
  - Implemented as fractional change in lepton resolution
  - 1σ = 2.5%, 5%, 10%, 20%
  - $\sigma_{\nu\mu}$= 1, $\sigma_{\bar{\nu}/\nu}$= $1\sigma \oplus 1\sigma$, $\sigma_{\nu e/\nu\mu}$= 100, $\sigma_{\nu\tau/\nu\mu}$= 100
- LepBias
  - Implemented as simple nonlinearity: $(1 + \sigma) *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

Also consider combinations of these with M_A^{QE} and M_A^{Res} to study possible conspiracies

Notes on correlations

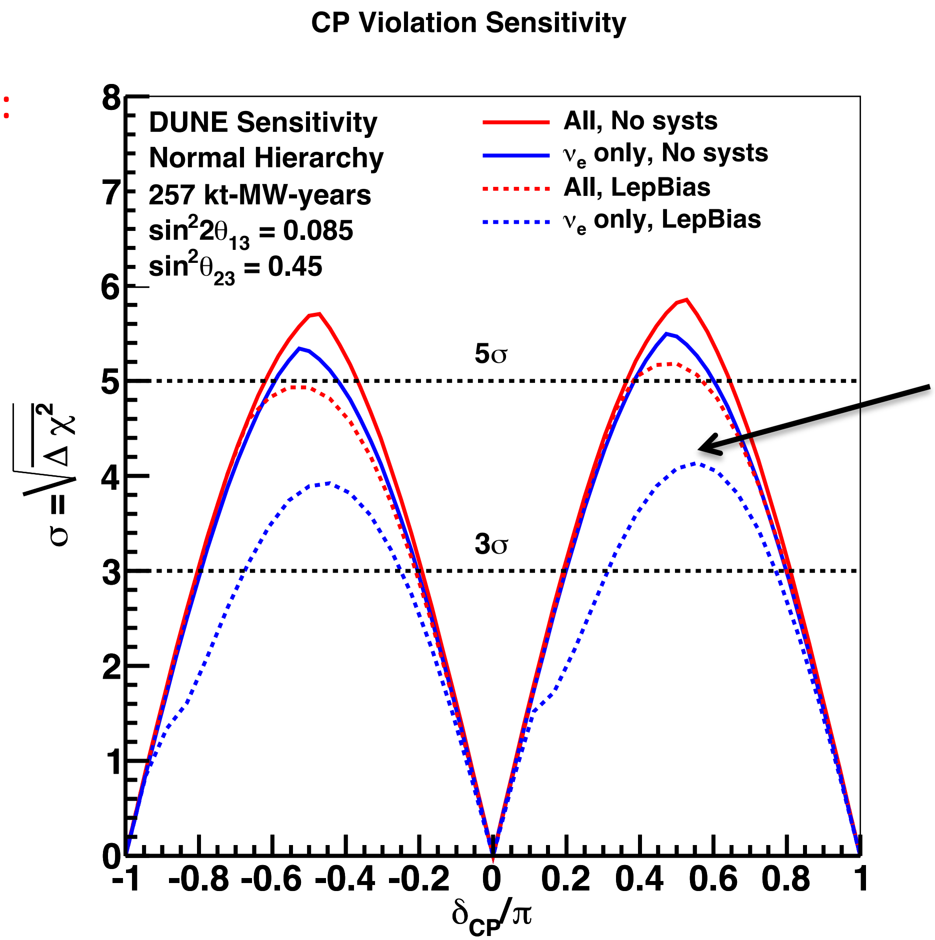
- Penalty terms constrain variation between neutrinos and antineutrinos and ν_e/ν_μ
- For (eg) cross-section uncertainty, this represents theoretical uncertainty
- For detector effects, we can (presumably) measure all of these independently so this factor estimates the relative uncertainties among these measurements
- Significant effect on results: input required from reconstruction and calibration groups to firm up the inputs for these quantities
- General principles so far:
  - ν_e/ν_μ uncorrelated for lepton effects
  - $\nu/\bar{\nu}$ uncorrelated for hadron effects (pessimistic)
  - Correlations assume that quantities can be measured in multiple modes with equal precision, so the relative uncertainty is taken as the quadrature sum

Sample CPV Sensitivity Fit: LepBias



Sample CPV Sensitivity Fit: LepBias

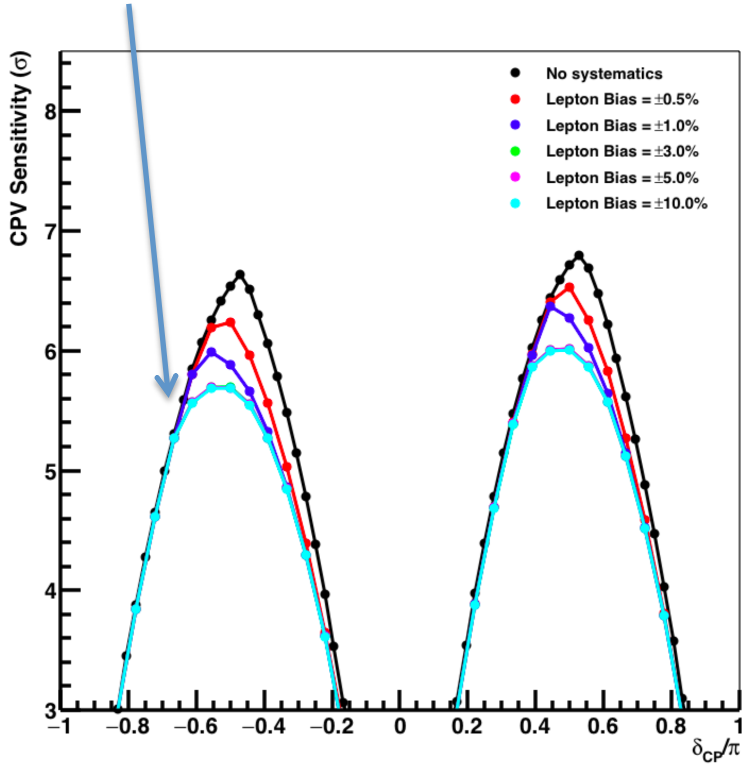
Previous study with different assumptions: not for direct comparison with current results

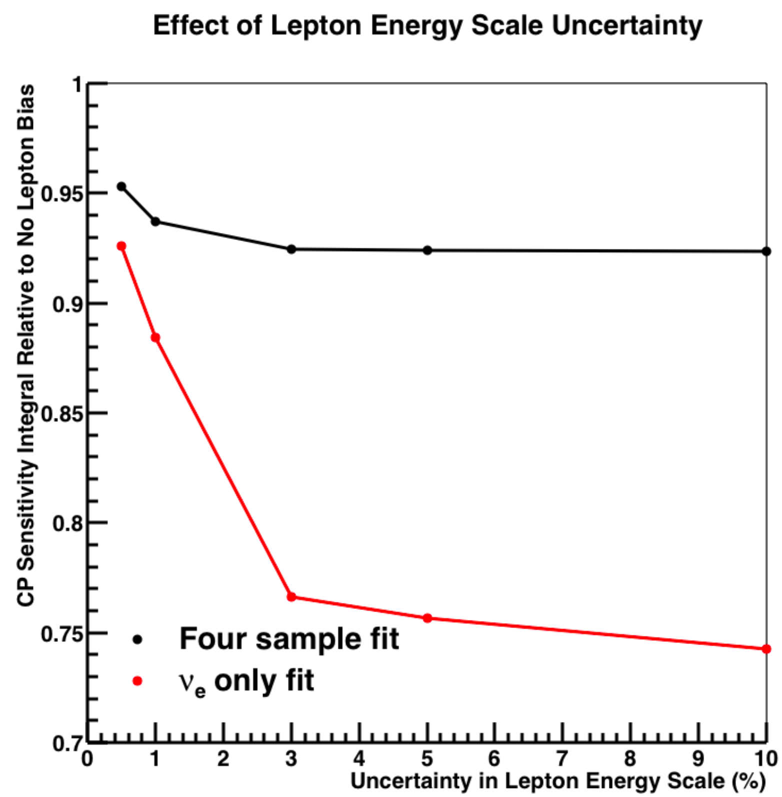


ν_e only fit has serious degradation: we rely on the constraint from antineutrinos in the 4-sample fit

Lepton Bias

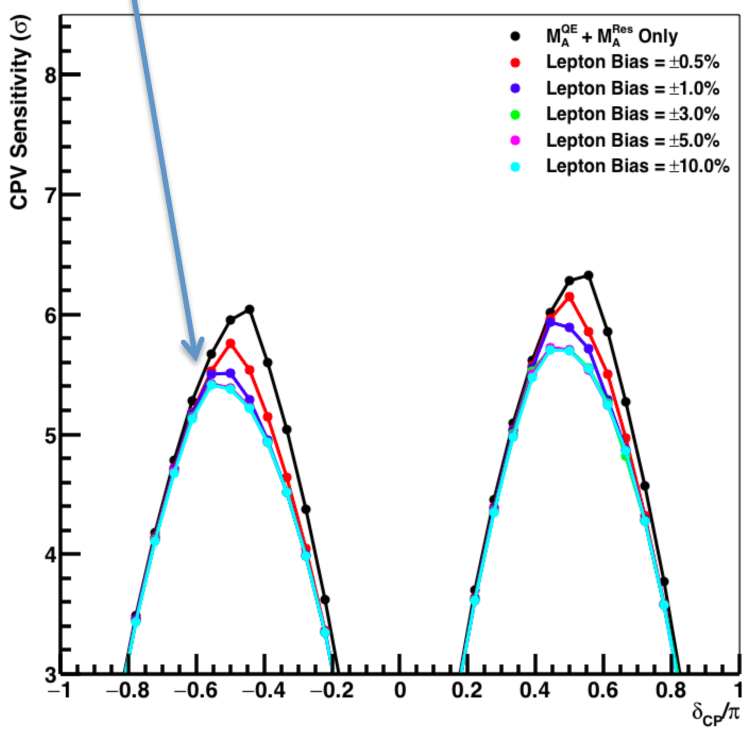
No effect for uncertainty >3%

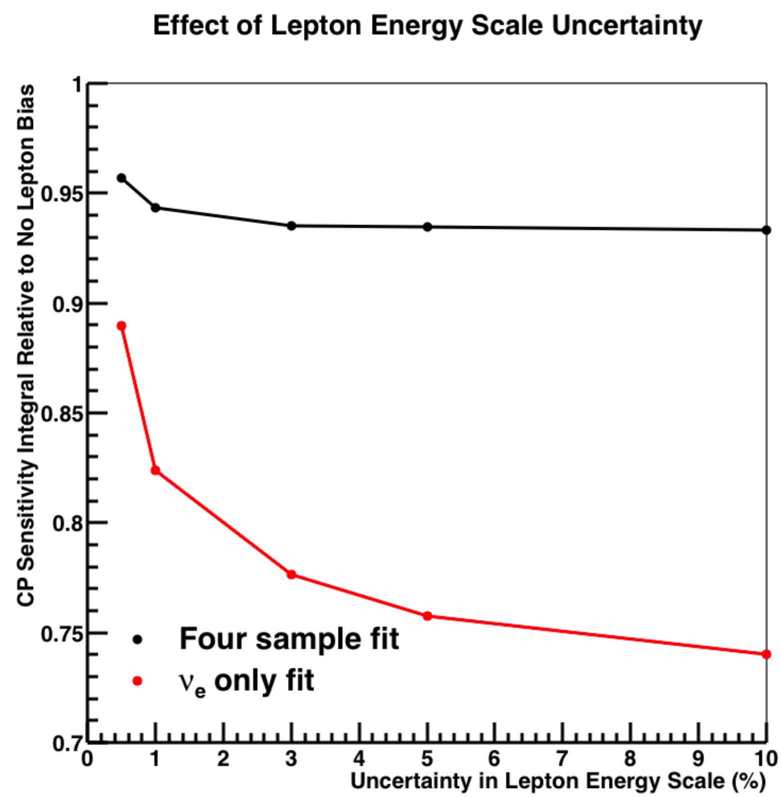




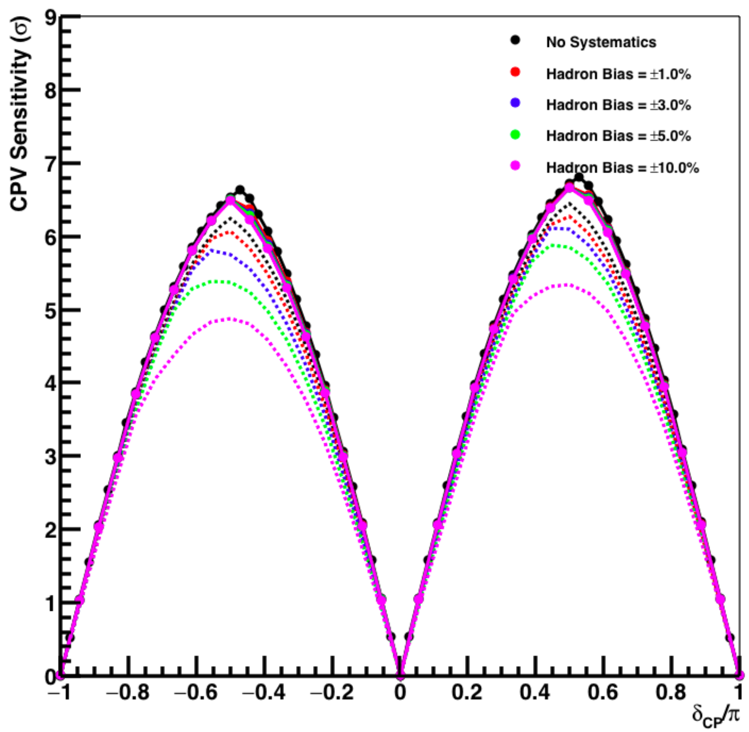
Cross-section + Lepton Bias

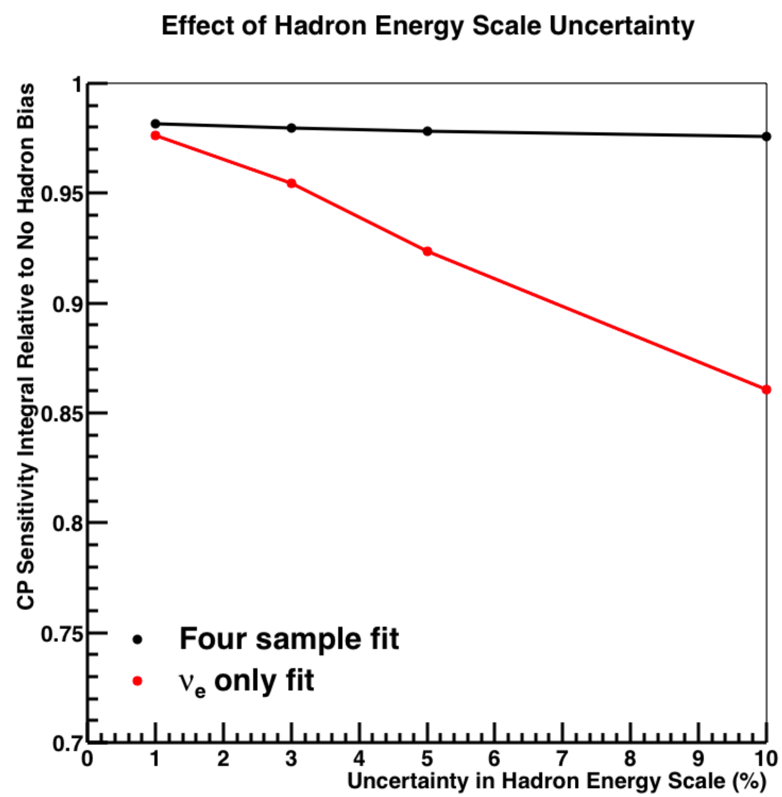
Similar conclusion





Hadron Bias

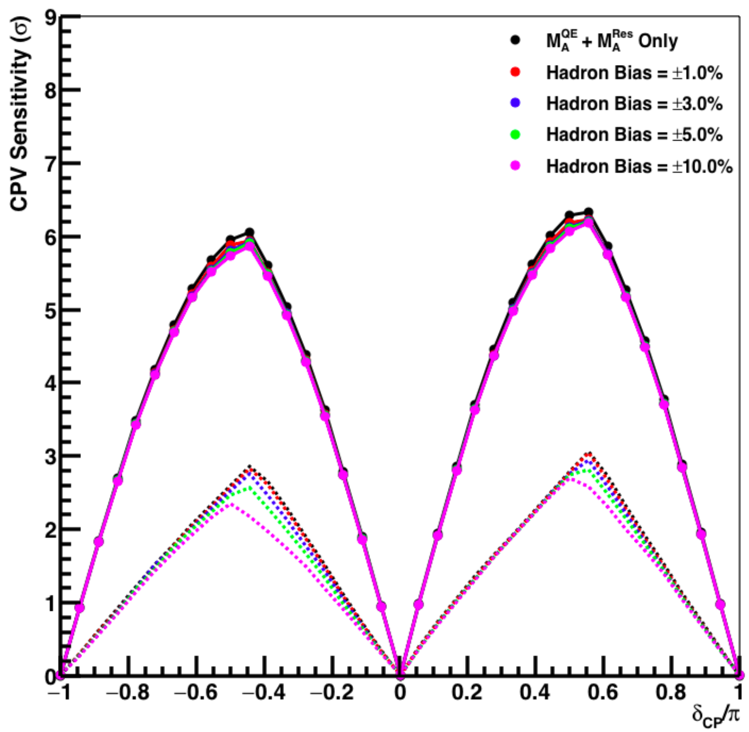


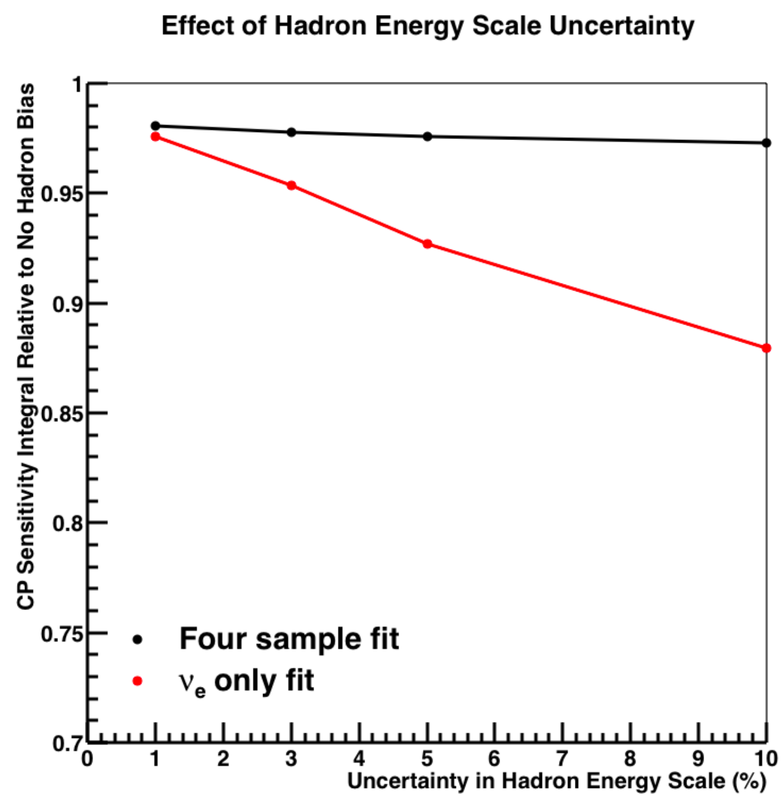


Solid = 4 sample

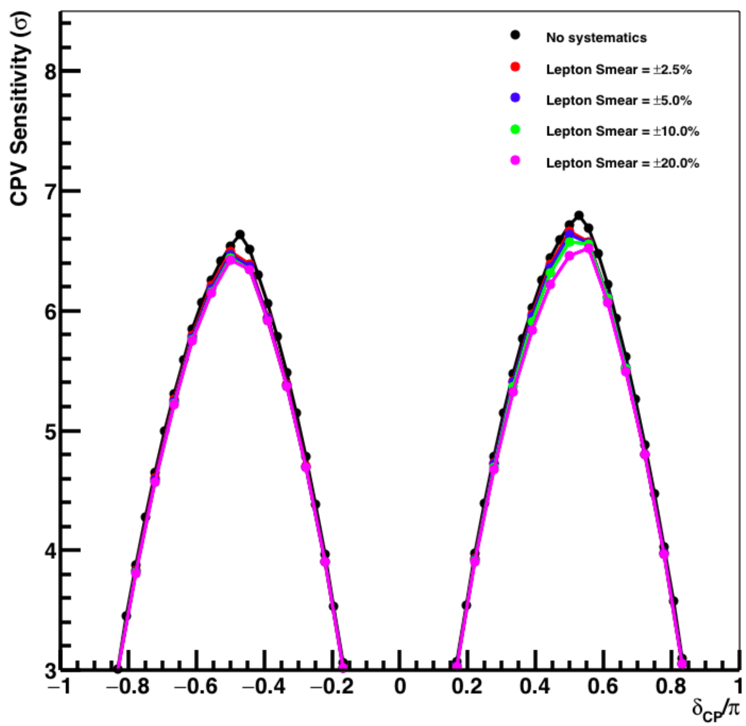
Dashed = ν_e only

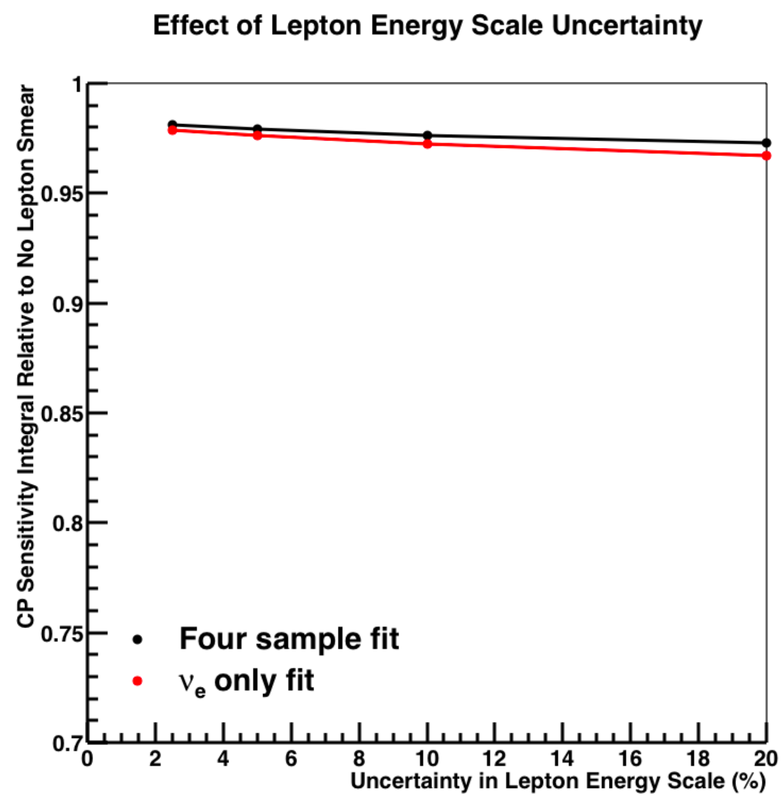
Cross-Section + Hadron Bias





Lepton Smearing





Summary

- Lepton energy scale uncertainty is most significant effect
- Need to determine lepton energy scale to better than 3% to improve sensitivity of 4-sample fit
- Ideally, lepton energy scale better than 1% (difficult!)
- There's a lot of phase space – not just a simple scan over individual parameters:
  - Effect of correlations
    - More thought/feedback needed to determine appropriate values
- New machinery required to correctly explore combinations of detector systematics and interface with LOAF – plan exists but no active work yet
- So far considering high level effects; will eventually want to study lower level calibration uncertainties