# SYSTEMATICS IN LONG-BASELINE OSCILLATION MEASUREMENTS

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# Introduction

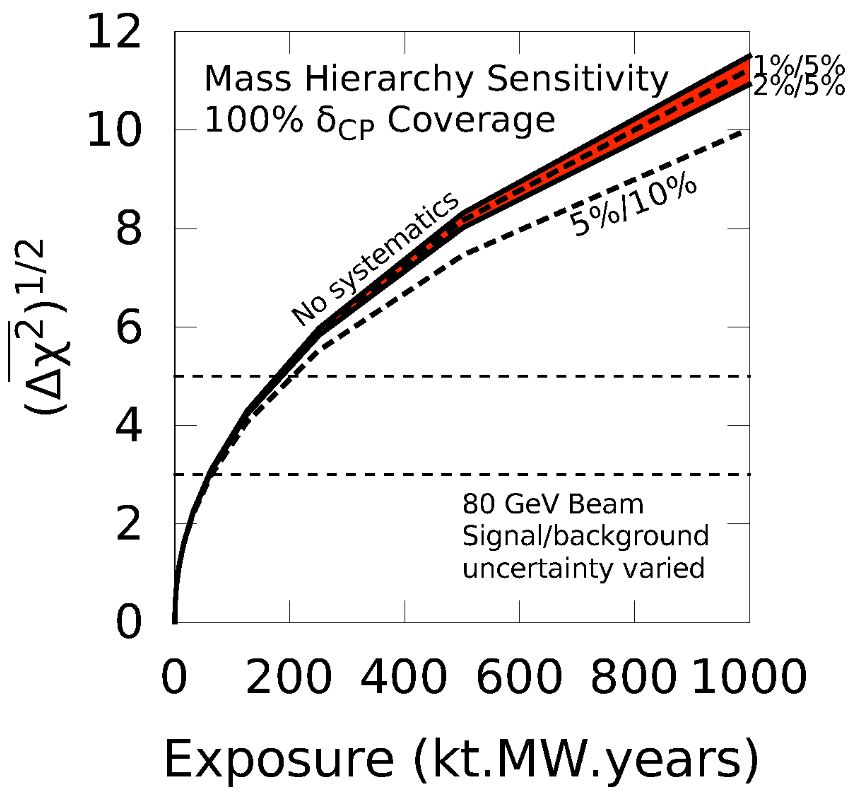
- Systematic uncertainties in LBNE have historically been treated in sensitivity studies using uncorrelated signal and background uncertainties in GLoBES, which represent the residual uncertainty that remains after constraints from the near detector and a four-sample fit at the far detector are applied. Values are chosen based on experience with past/current experiments. Energy scale uncertainty not yet included.
- Current focus is on studying effect of individual sources of systematic uncertainty
  - Flux determination
  - Cross section and nuclear models
  - Detector effects
  - Systematics affect both normalization and energy scale

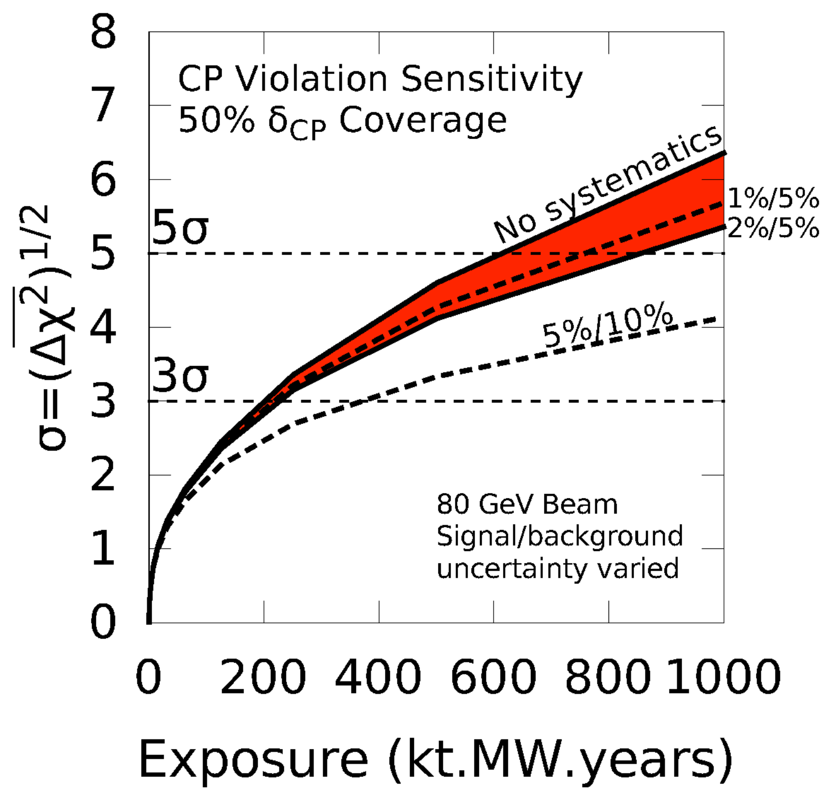
# Systematics in GLoBES

- Sensitivity calculations are a joint fit to $\nu_e$ appearance and $\nu_\mu$ disappearance with equal running in neutrino and antineutrino mode
- Signal and background 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
- Nominal values of uncorrelated residual normalization uncertainties:
  - $\nu_e$ appearance: 1% signal, 5% bg
  - $\nu_\mu$ disappearance: 5% signal, 10% bg

Often quote uncorrelated uncertainty for appearance mode only,
but disappearance uncertainty is always included.

# GLoBES Sensitivity Calculations




- Actual experimental sensitivity to systematic uncertainty will depend on details of the neutrino beam and detector performance and will include both normalization and shape uncertainty
- Example shown here illustrates that control of normalization uncertainty at the few % level will be needed for discovery of CP violation at the 5$\sigma$ level

# Individual Systematic Effects

Systematics Goals Based on Prior Experience:

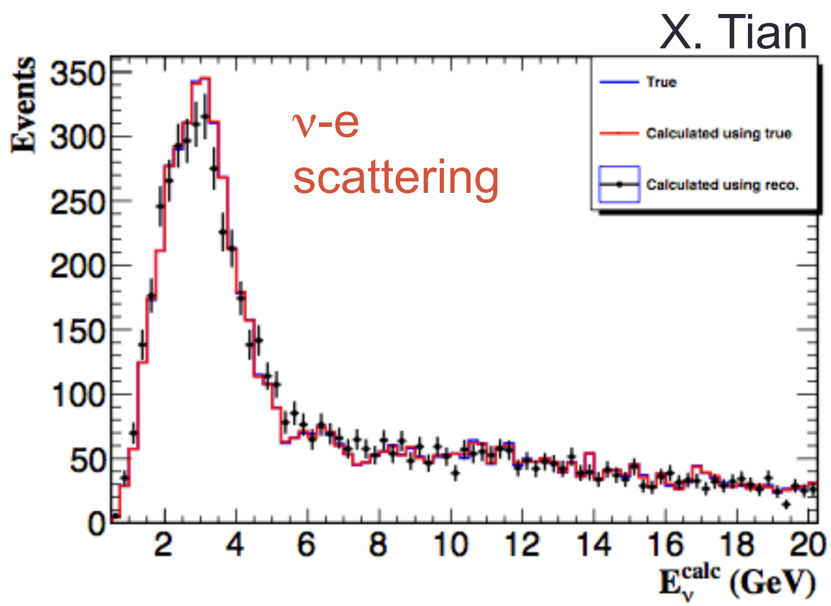
| Source of Uncertainty | MINOS $\nu_e$ | T2K $\nu_e$ | ELBNF $\nu_e$ | Comments |
|---|---|---|---|---|
| Beam Flux after N/F extrapolation | 0.3% | 2.9% | 2% | MINOS is normalization only. ELBNF normalization and shape highly correlated between $\nu_\mu/\nu_e$. |
| Neutrino interaction modeling | | | | |
| Simulation includes: hadronization cross sections nuclear models | 2.7% | 7.5% | $\sim 2\%$ | Hadronization models are better constrained in the ELBNF LArTPC. N/F cancellation larger in MINOS/ELBNF. X-section uncertainties larger at T2K energies. Spectral analysis in ELBNF provides extra constraint. |
| Detector effects | | | | |
| Energy scale ($\nu_\mu$) | 3.5% | included above | (2%) | Included in ELBNF $\nu_\mu$ sample uncertainty only in 3-flavor fit. MINOS dominated by hadronic scale. |
| Energy scale ($\nu_e$) | 2.7% | 3.4% includes all FD effects | 2% | Totally active LArTPC with calibration and test beam data lowers uncertainty. |
| Fiducial volume | 2.4% | 1% | 1% | Larger detectors = smaller uncertainty. |
| Total | 5.7% | 8.8% | 3.6 % | Uncorrelated $\nu_e$ uncertainty in full ELBNF 3-flavor fit = 1-2%. |

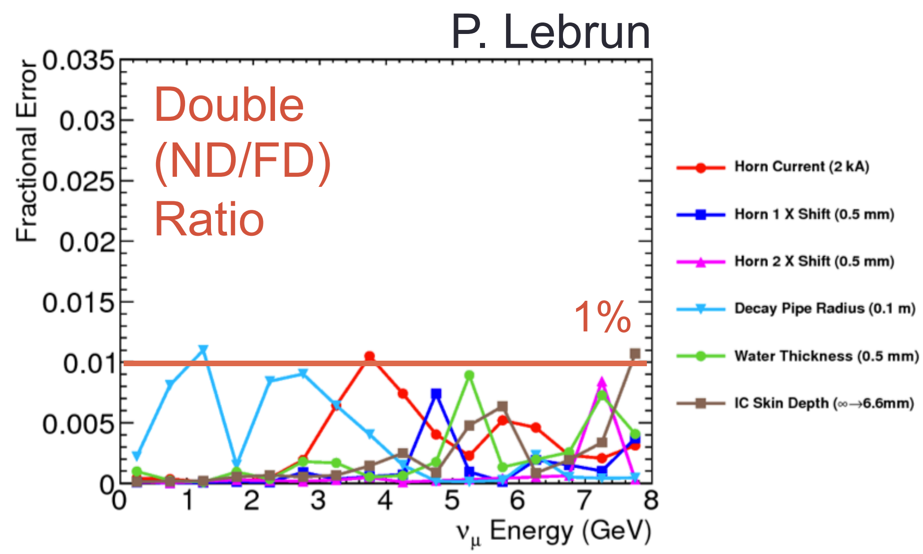
The projected uncertainties in ELBNF are chosen by determining which of the existing experiments is more representative of ELBNF for each source of systematic uncertainty and then setting the reasonable goal that a next generation experiment, with the high resolution of a LArTPC and precise measurements from a highly capable near detector, should be able to improve on a similar earlier experiment.

- Characterization of individual sources of systematic uncertainty has been the primary focus of the LBNE long-baseline physics working group for the past year
  - Initial results use Fast MC and VALOR/MGT to study systematics constraints from both near and far detector event samples
  - CETUP*2014 systematics workshop led to detailed plan of study
  - arXiv:1501.05054 (CETUP* Proceedings: Systematics Summary) provides short summary of status and plans
  - New version of GLoBES allows more sophisticated treatment of systematic uncertainty – in development for ELBNF
  - This talk will show some examples of recent and in-progress work but can not address the full plan

# Flux Uncertainty

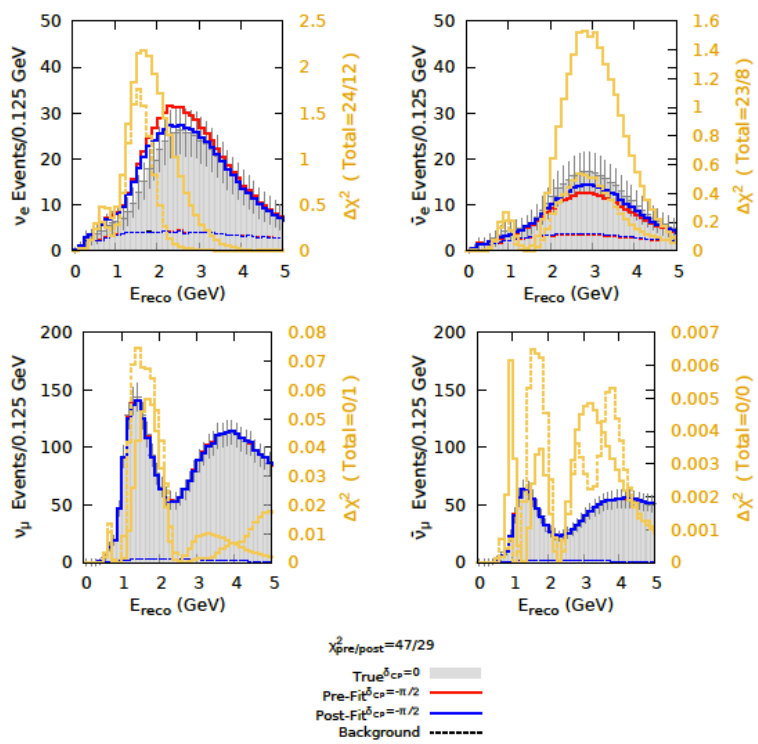
- Flux determination studied using Fast MC simulation of FGT near detector
  - Absolute normalization based on fully leptonic neutrino interactions (2-3%)
  - Flux shape determination based on low $n_0$ method (1-2%)
  - More detailed treatment of systematic uncertainty in these studies in progress
  - More detailed understanding of requirements for ND performance and ND-FD relative calibration to achieve these constraints is needed
- Beam optics systematics study allows position of beamline elements to vary within design specs based on experience with NuMI: finds 1% effect in ND/FD
  - Some caveats apply, but this is not expected to be a leading effect
- Unconstrained uncertainty in hadronization model order 10%
  - More on slide 8…



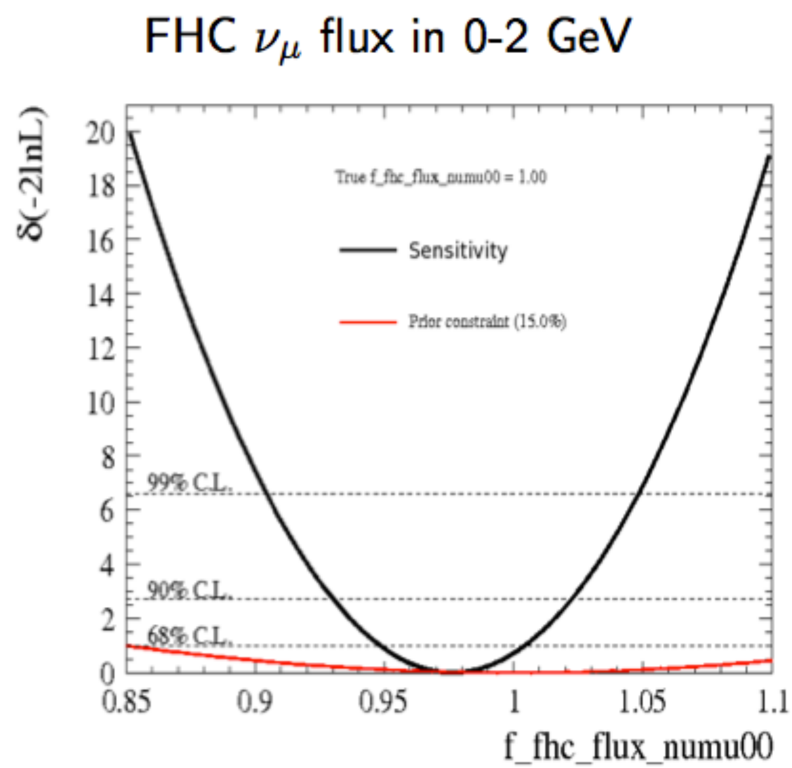
# Constraining Flux Uncertainty

## Beam Optics Variations in FastMC (no ND constraint):




No surprise that ND is needed to constrain flux!

## Example: Constraining flux with ND in VALOR:

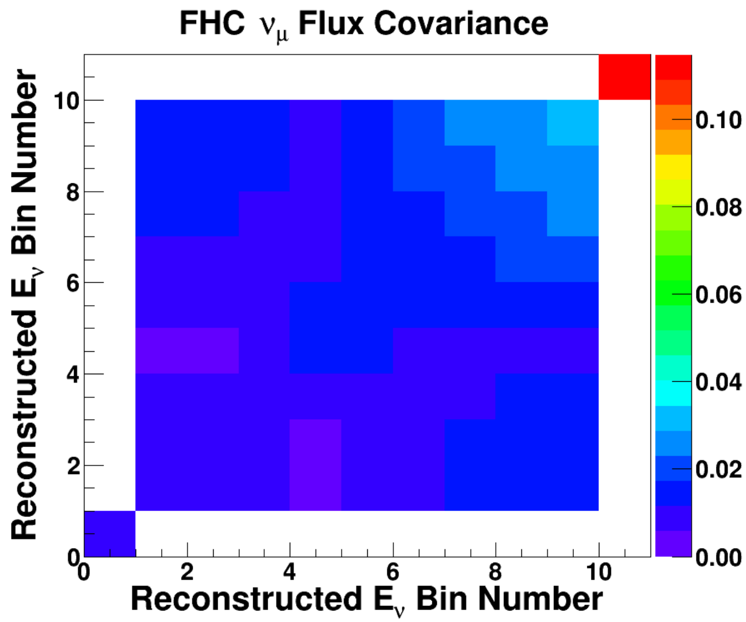



No surprise that ND provides significant flux constraint!

# Hadronization Model Studies

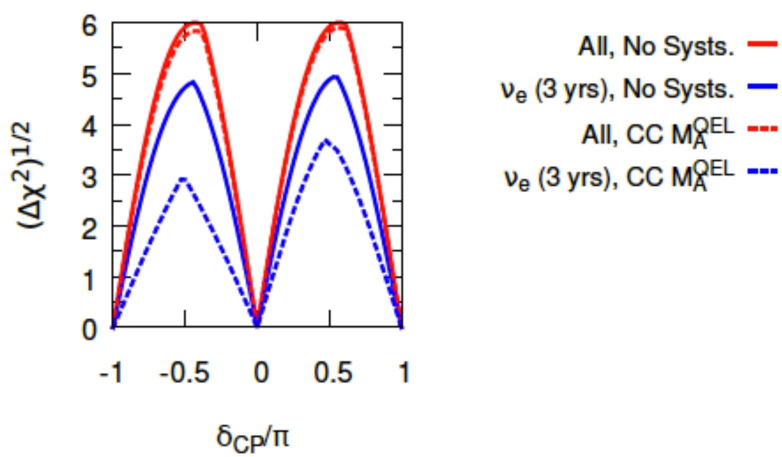
- Uncertainties order 10%, not yet fully explored by FastMC
- Implementation of flux driver (GENIE) and Minerva flux reweighting tools for LBNE flux simulations in progress
- Interim studies: vary simulated flux based on Minerva uncertainties in NuMI flux, starting with simple uncertainties and building towards more sophisticated variations, including bin-to-bin correlations
  - Preliminary flux covariance matrixes obtained from Minerva data
  - Implementation of systematics treatment using flux covariance matrixes in MGT in progress

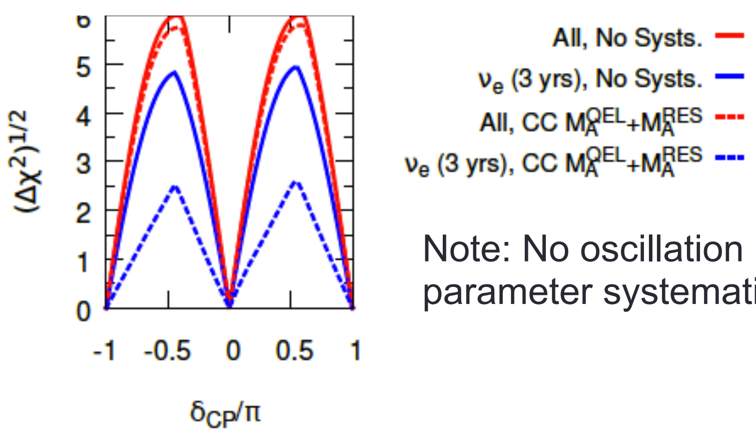
Example of NuMI flux covariance matrix, based on arXiv:1409.3835 and work from D. Cherdack and L. Fields.



# Cross Sections: FD Constraints

Example: CPV Sensitivity (FastMC):



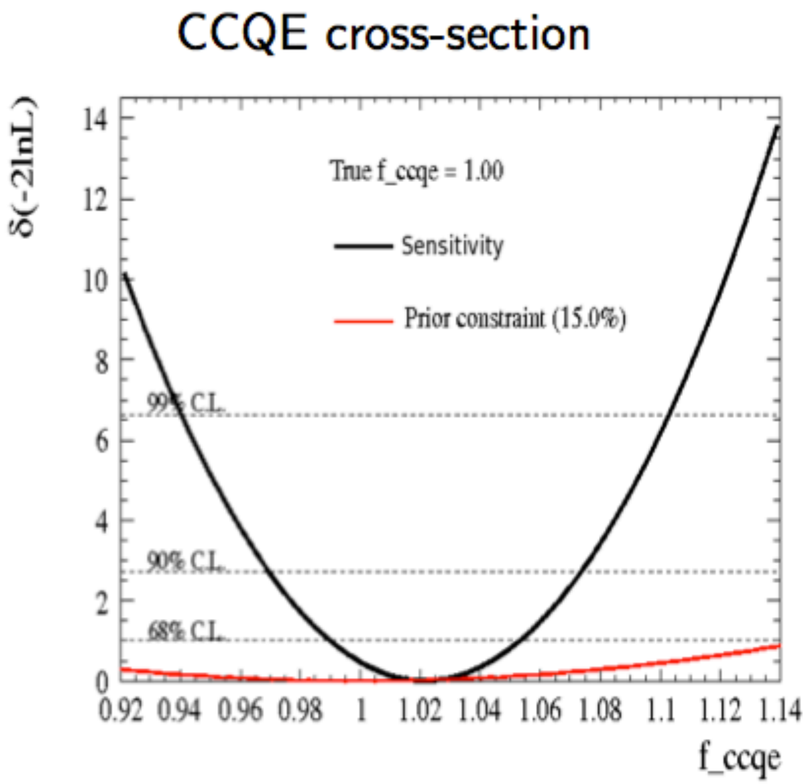



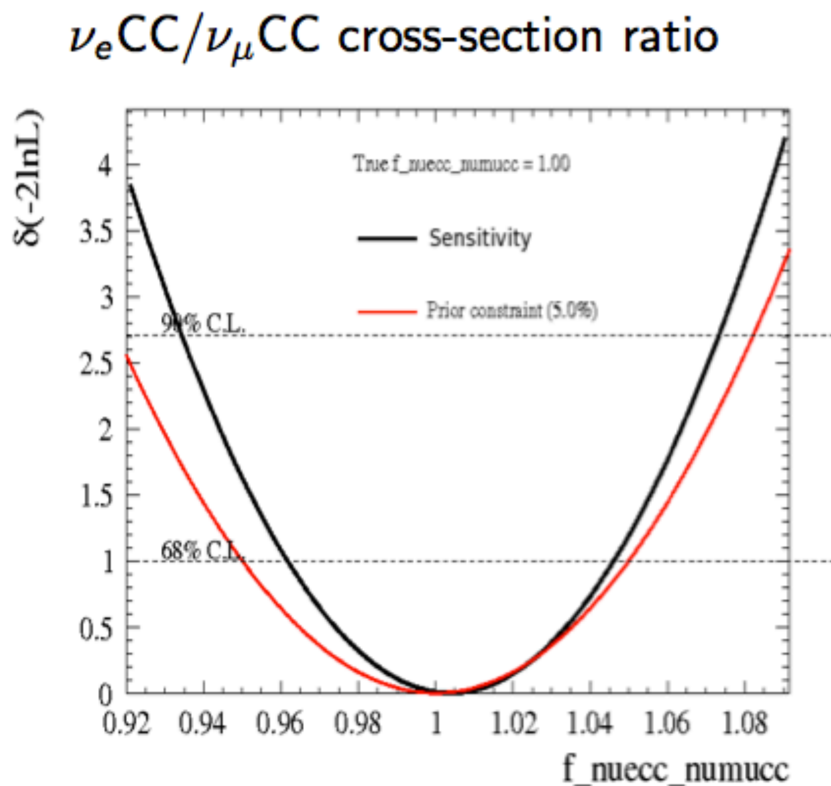

Note: No oscillation parameter systematics

- FastMC with **no** ND constraints
  - Vary cross-section parameters within GENIE uncertainties
- Significant degradation in sensitivity for fit to only $\nu_e$ appearance sample for a single cross-section systematic uncertainty
- Fit to all four FD samples significantly constrains cross-section variations leading to very little degradation in sensitivity for same cross-section uncertainty
- Starting to look at combinations of cross-section parameter variations
  - eg: $M_A^{QE}$ and $M_A^{RES}$
  - So far, cancellations encouraging
  - Full suite of systematic studies coming
  - Computing challenge combining all systematics, investigating MCMC to improve parallelization of MGT

# Cross Sections: ND Constraints

Example: Constraining cross-sections with ND in VALOR:




Important to understand cases in which ND does **not** provide significant constraint. What external constraints are available? Additional external info needed? Better ND performance needed?

# Cross-section and nuclear models: Beyond current uncertainties

- Basic strategy is to compare Fast MC observables among alternative models in GENIE
  - 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
- Comparison with alternative generators (NuWro, GiBUU)

In various stages of implementation in GENIE. Requires close collaboration with GENIE and with model builders.

# Far Detector Uncertainty

- Detector performance inputs to Fast MC
  - Lepton resolutions
  - Hadron resolutions
  - Energy scale
  - Signal efficiency
  - e-$\gamma$ separation

Based on "conventional wisdom":
- GENIE kinematics
- ICARUS results
- LArSoft hand scans
- $\mu$BooNE LArSoft studies

- Improving inputs to Fast MC:
  - 35t prototype and $\mu$BooNE data coming soon
  - LArIAT, CAPTAIN, LAr1-ND, CERN neutrino platform prototypes…
  - Structure for sharing information among collaborations needed
- Implementation of energy resolution and scale variations in Fast MC in progress
  - Intermediate implementation done – sensitivity studies in progress
  - Full implementation in progress
  - Allows quantification of detector performance requirements
- Implementation of more sophisticated analysis algorithms in Fast MC in progress
  - NC and $\nu_\tau$ rejection using kNN algorithm in progress
  - Update to e-$\gamma$ separation efficiency in progress, ultimately BDT method?

# Cavern Optimization (Preliminary)

- Study acceptance (relative to nominal fiducial volume) given reconstruction requirements:
  - Electrons: shower containment fraction
  - Muons: momentum resolution from multiple Coulomb scattering
- Inputs:
  - Momentum vs. lepton angle from GENIE kinematics
  - Electron shower longitudinal profile from uBooNE study (J. Huang)
  - Muon resolution vs. track length from uBooNE study (L. Kalousis)
- Compare two (currently outdated) cavern designs:
  - 2 x 5 kt + 2 x 12 kt (2 cavern)
  - 2 x 17 kt (1 cavern)
  - Does not yet include effect of gaps – only distance from detector edge
- Preliminary result (electrons): <1% acceptance difference even for 100% shower containment
- Muons: In progress
- Other samples ($\pi^0$, Michel electrons, proton decay modes) will also be studied
- Last step is to select resolution requirements based on sensitivity studies

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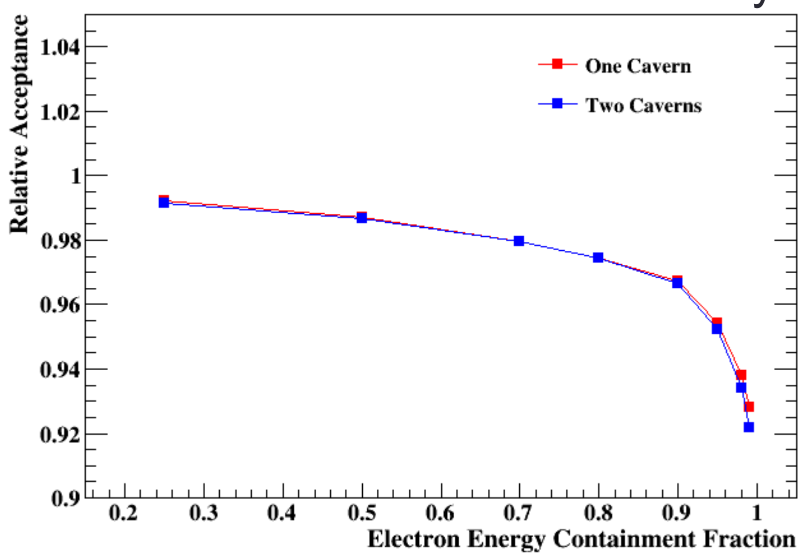

# Summary

- First pass at a complete evaluation of systematic uncertainty / detector performance requirements in ELBNF is needed ASAP.
- Initial studies using GENIE uncertainties show very promising constraints on systematic uncertainty from both FD & ND samples.
- Detailed plan to evaluate sources of systematic uncertainty not currently considered by FastMC and VALOR studies has been developed. Tools are ready to use and experts are ready and willing to help people get started using the tools.
- Significant additional effort is needed – please join us in studying systematic uncertainty!
- ELBNF detector design is not final: **systematics-driven detector performance requirements will guide detector design.** Long-baseline systematics requirements will also be an important factor in ND design choices and optimization.