Neutrino Interaction Systematics and Future Long-Baseline Searches for Mass Hierarchy and CP Violation

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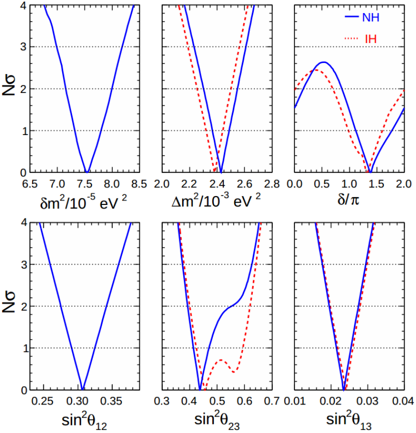
Overview

- Mass hierarchy (MH) and CP violation (CPV) in future long-baseline (LBL) experiments
  - LBL neutrino oscillations
  - T2HK (briefly), LBNE, LBNO
- Method, statistics, and systematics for sensitivity to MH and CPV
  - Focus on methods and effects of systematics. No attempt made to compare on equal footing or to account for possible phasing of the experiments.
  - Normalization uncertainties in LBNE and LBNO
- Example: LBNE's approach to computing sensitivity and incorporating detailed systematic uncertainties
  - The LBNE Fast Monte Carlo simulation
  - Fast MC systematic response functions
  - Near detector strategy to constrain systematics

Long-Baseline Oscillations

- **Large θ_{13}** from both ν_e appearance and $\bar{\nu}_e$ disappearance experiments
  - Possibility of observing CP violation
- **Global fits** produce strong constraints on many of the PMNS matrix parameters
- Will focus on the least constrained:
  - δ_{CP} and **CP violation** ($\sin(\delta_{CP}) \neq 0$)
  - **Mass hierarchy**: **normal** or **inverted**?
- Experiments with LBL (matter-effect) and high-statistics necessary to look for these oscillation effects in
  - $\nu_\mu \rightarrow \nu_e$ appearance
  - $\nu_\mu \rightarrow \nu_\mu$ disappearance

Capozzi et al [arXiv:1312.2878v2]



Global fit of PMNS matrix parameters to LBL, Solar, Kamland, Reactor, and atmospheric measurements assuming either normal or inverted hierarchy

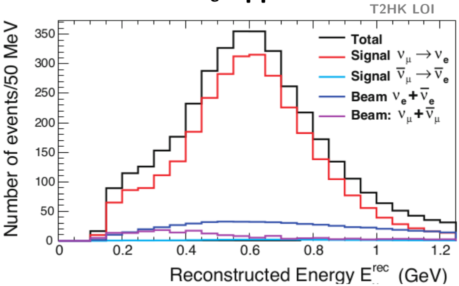
Future LBL Experiments: T2HK

- Tokai to Hyper-K (T2HK) LBL physics:
- ***L***: 295 km
- $\boldsymbol{E_\nu}$: 0.6 GeV (off-axis)
  - Narrow-band beam
- **Total POT**: 1.56×10^{22}
- **Far Detector**: 560 kt (fiducial) WC

Table: Event rates for 560 kt, 7.5 MW * 10^7 s $\sin^2(2\theta_{13}) = 0.1$ and $\delta_{CP} = 0$

	CC $\nu_\mu \rightarrow \nu_e$	Total BG
25% ν mode	3044	706
75% $\bar{\nu}$ mode	2506	892

T2HK ν_e appearance



Future LBL Experiments: LBNE

- Long-Baseline Neutrino Experiment (LBNE) LBL Physics:
- ***L***: 1300 km
- $\boldsymbol{E_\nu}$: 0.5-8 GeV
  - Wide-band beam
- **Total POT**: 9×10^{21} POT
- **Far Detector**: 34 kt (fiducial) LAr TPC

LBNE ν_e appearance
34 kt * 3 yrs

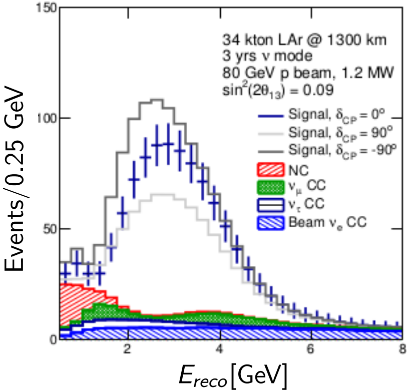


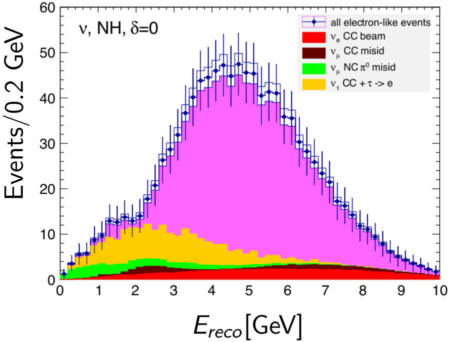
Table: Event rates for 34 kt, 1.2 MW, 6 years with $\sin^2(2\theta_{13}) = 0.09$ and $\delta_{CP} = 0$

	CC $\nu_\mu \to \nu_e$	Total BG
50% ν mode	789	364
50% $\bar{\nu}$ mode	190	187

Future LBL Experiments: LBNO

- Long-Baseline Neutrino Oscillation (LBNO) Experiment LBL Physics:
- ***L***: 2300 km
- $\boldsymbol{E_\nu}$: 1-10 GeV
  - Wide-band beam
- **Total POT**: 1.5×10^{21} POT
- **Far Detector**: 20 kt (fiducial) LAr TPC

LBNO ν_e appearance
20kt * 7.5 yrs



Agarwalla et al, arXiv:1312.6520v3

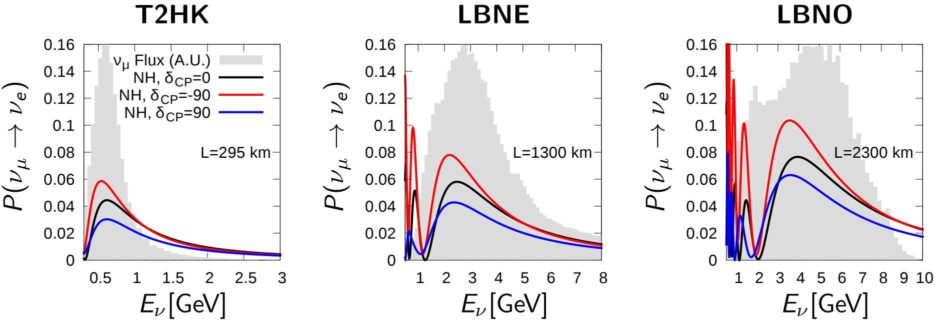
Beam	ν_μ unosc. CC	ν_μ osc. CC	ν_e beam CC	ν_μ NC	$\nu_\mu \to \nu_\tau$ CC	$\nu_\mu \to \nu_e$ CC $\delta_{CP} = -\pi/2$,	0,	$\pi/2$
LBNO: 2300 km NH 400 GeV, 750 kW 1.5×10^{20} POT/year								
50kt years ν	3447	907	22	1183	215	246	201	162
50kt years $\bar{\nu}$	1284	330	5	543	98	20	27	29

Expected events at 50 kt.year in ν and $\bar{\nu}$ modes

ν_e Appearance: CP Violation

$$P_{\nu_\mu \to \nu_e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1-x)\Delta)}{(1-x)^2}$$
$$- \alpha \sin 2\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin((1-x)\Delta)}{(1-x)}$$
$$+ \alpha \sin 2\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin((1-x)\Delta)}{(1-x)}$$
$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$x = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$
$$\Delta = \frac{\Delta m^2_{31} L}{4E}$$
$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$



ν_e Appearance: Mass Hierarchy

$$P_{\nu_\mu \to \nu_e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1-x)\Delta)}{(1-x)^2}$$
$$- \alpha \sin 2\theta_{13} \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \frac{\sin(x\Delta)}{x} \frac{\sin((1-x)\Delta)}{(1-x)}$$
$$+ \alpha \sin 2\theta_{13} \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \frac{\sin(x\Delta)}{x} \frac{\sin((1-x)\Delta)}{(1-x)}$$
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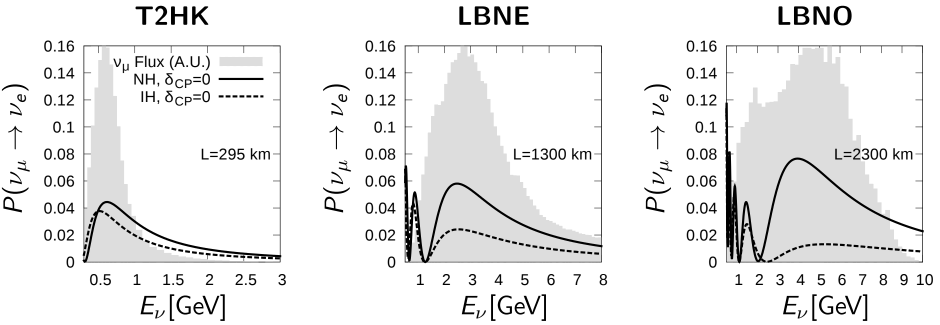


Simulating the Experiments

- **T2HK**: very similar to T2K, but some differences
  - Beam upgrade, event rates in the near detector
  - Upgrades to near detector(s)
  - FD has lower PMT coverage (SK2)
- **LBNE and LBNO**: have similar challenges
  - State of the art detector technologies come with reconstruction challenges
  - ND design still uncertain
    - Identical vs high resolution detectors
    - Methods of propagating constraints to the FD

Statistics for MH and CPV Sensitivity

- Quantify experimental sensitivity using χ^2 (ratio of Poisson likelihoods):

$$\chi^2\left(\boldsymbol{\theta}_{true}, \boldsymbol{\theta}_{test}, \boldsymbol{f}\right) = 2 \cdot \sum_{i}^{N_{bins}} \left(n_i^{true} \cdot \ln \frac{n_i^{true}}{n_i^{test'}} + n_i^{test'} - n_i^{true} \right) + \sum_{j}^{N_{systs}} \frac{f_j^2}{\sigma_j^2}$$

- $\boldsymbol{n}^{true}$: Sig.+BG events for $\boldsymbol{\theta}_{true}$ oscillation parameters
- $\boldsymbol{n}^{test'}$: Sig.+BG events for $\boldsymbol{\theta}_{test}$ oscillation parameters and $\boldsymbol{f}$ systematic parameters
  - $\boldsymbol{f}$ encodes all allowed systematic variations and is constrained by priors ($\boldsymbol{\sigma}$)

Mass Hierarchy Statistic

- $\Delta\chi^2_{MH} = \chi^2(NH, IH) - \chi^2(NH, NH)$
- No stat. fluctuations: $\Delta\chi^2_{MH} = \chi^2(NH, IH)$

CP Violation Statistic

- $\Delta\chi^2 = \text{Min}[\chi^2(\delta_{CP}^{true}, \delta_{CP}^{test} = 0), \chi^2(\delta_{CP}^{true}, \delta_{CP}^{test} = \pi)]$
- $\sqrt{\Delta\chi^2} \approx \sigma$

Normalization Uncertainties in LBNE

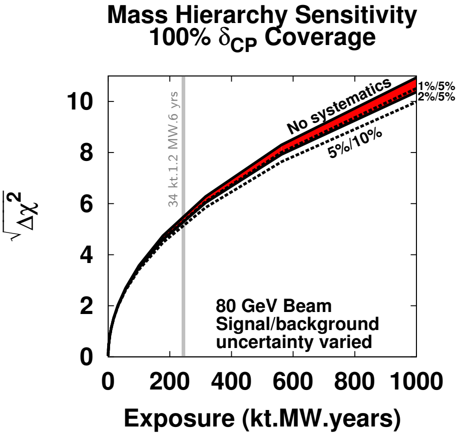
- Total sensitivity given by joint fit of ν_e appearance and ν_μ disappearance in ν and $\bar{\nu}$ modes
  - Each χ^2 minimized with respect to systematics parameters

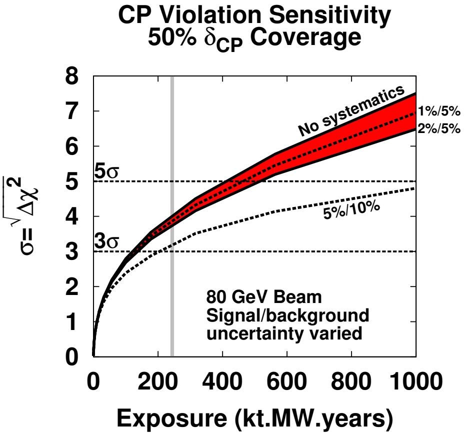
$$\chi^2_{total} = \chi^2_{\nu_e\ App.} + \chi^2_{\bar{\nu}_e\ App.} + \chi^2_{\nu_\mu\ Disapp.} + \chi^2_{\bar{\nu}_\mu\ Disapp.}$$

Nominal: normalization systematics

- 1% on signal, 5% on total background in ν_e, $\bar{\nu}_e$ appearance
- 5% on signal, 10% on total background ν_μ, $\bar{\nu}_\mu$ disappearance
- Uncorrelated among ν_e appearance, $\bar{\nu}_e$ appearance, ν_μ disappearance, $\bar{\nu}_\mu$ disappearance samples
  - Residual uncertainties assuming that correlated pieces cancel
  - Ongoing studies will justify/update these estimates

LBNE Sensitivity & Norm. Uncertainties





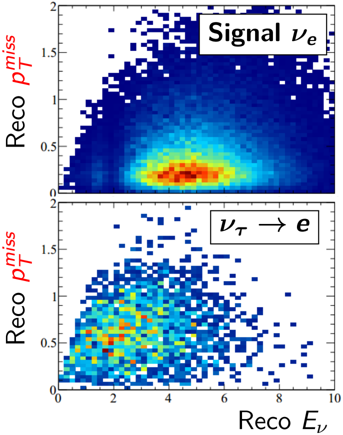
- No systematics and normalization systematic uncertainties on signal/background from 1%/5% to 5%/10%
- Exposures less than 100 kt.MW.years are statistically limited
- Small effect for MH (due to shape) but significant effect for CPV

Normalization Uncertainties in LBNO

$$\chi^2\left(\boldsymbol{\theta}_{true}, \boldsymbol{\theta}_{test}, \boldsymbol{f}\right) = 2 \cdot \sum_{i}^{N_{reco}, p_T^{miss}} \left(n_i^{true} \cdot \ln \frac{n_i^{true}}{n_i^{test'}} + n_i^{test'} - n_i^{true} \right) + \sum_{j}^{N_{systs}} \frac{f_j^2}{\sigma_j^2}$$

Nominal: normalization systematics

- 5% on signal normalization
- 5% on beam ν_e background
- 20% on ν_τ background (for CP violation sensitivities)
- 10% NC and ν_μ CC background
- Correlated across analysis samples



Agarwalla et al, arXiv:1312.6520v3

LBNO Sensitivity & Norm. Uncertainties

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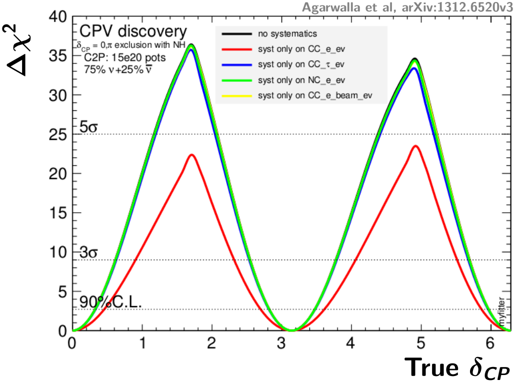


- Effects for each systematic on CP violation sensitivity
  - Largest effect from signal normalization uncertainty

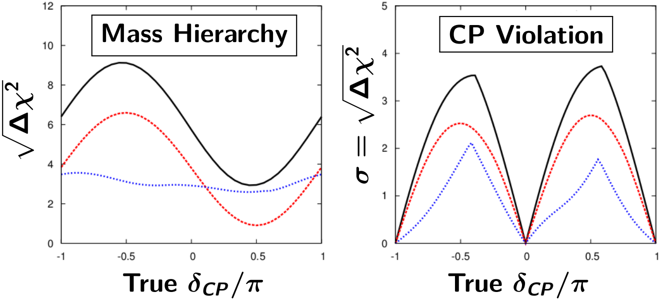
Beyond Normalization Systematics

- Normalization systematics encompass part of uncertainties but do not degrade **shape information**
- Analyses in LBNO and LBNE (below) rely on **shape and rate**
  - Mostly rate in a narrow-band beam (T2HK)
- LBNE and LBNO are both performing detailed studies of the detector designs and requirements based on **MC simulations** for the near and far detectors
  - Including detailed effects of neutrino interaction systematics
- Will discuss the current state of **LBNE's simulation efforts**

LBNE

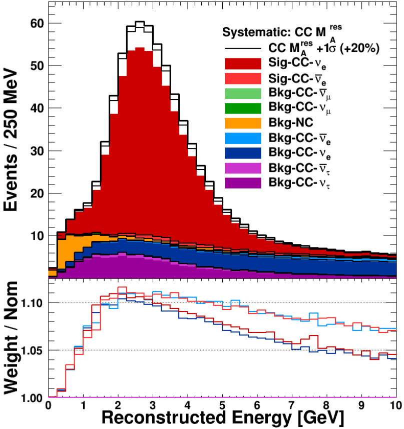
70 kt.MW.yrs

- **Shape+Rate**
- **Rate only**
- **Shape only**



LBNE Simulation: Fast MC

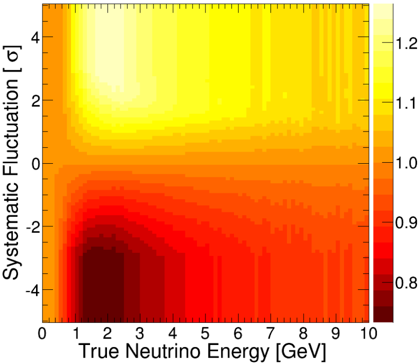
- LBNE is developing a Fast Monte Carlo (**Fast MC**) to characterize effects of uncertainties in flux, cross-sections, FSI, beamline tolerances, beam design optimizations, and energy scale/resolution
  - LBNE flux predictions, GENIE event generator, parameterized detector response
- Simulates **particle-by-particle** thresholds, missing energy, and smearing
- **Detector response** is parameterized by inputs from MicroBooNE simulations, GEANT4, and ICARUS
- Realistic kinematics used to build selections and **calorimetrically reconstruct energy**
  - p_T^{miss} cut for ν_τ BG reduction



- Example: nominal (filled area) ν_e appearance event spectrum and variation (line) induced by +20% change in **CC M_A^{res}**

Fast MC Response Functions

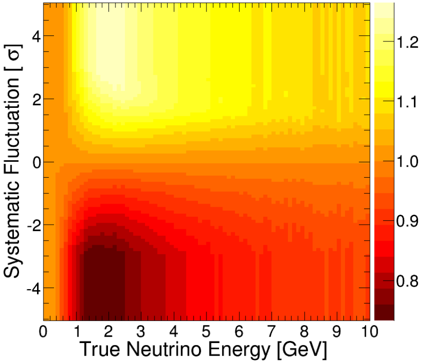
- Fast MC generates set of **systematic response functions** that encode variations in event selections produced by variations in
  - Cross sections
  - Nuclear Models
  - Flux uncertainties
  - Energy resolutions
- Example: **CC M_A^{res}** 1σ change ($+20\%$ change in parameter) produces a $+10\%$ change in number of signal ν_e events at 2 GeV



- Response (fractional change) of ν_e signal events in ν_e appearance analysis to changes in CC M_A^{res}

Fast MC Response Functions

- Fast MC generates set of **systematic response functions** that encode variations in event selections produced by variations in
  - Cross sections
  - Nuclear Models
  - Flux uncertainties
  - Energy resolutions
- Example: **CC M_A^{res}** 1σ change ($+20\%$ change in parameter) produces a $+10\%$ change in number of signal ν_e events at 2 GeV
- **Propagate systematic parameters in the flux, generator (GENIE), or detector response through to the oscillation sensitivities**



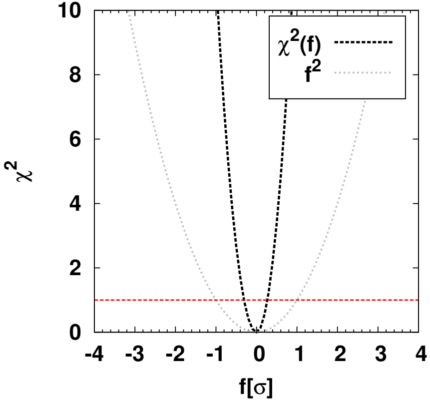
- Response (fractional change) of ν_e signal events in ν_e appearance analysis to changes in CC M_A^{res}

Response Functions and χ^2

$$\chi^2\left(\boldsymbol{\theta}_{true}, \boldsymbol{\theta}_{test}, \boldsymbol{f}\right) = 2 \cdot \sum_{i}^{N_{reco}} \left(n_i^{true} \cdot \ln \frac{n_i^{true}}{n_i^{test'}} + n_i^{test'} - n_i^{true} \right) + \sum_{j}^{N_{nuis}} \frac{f_j^2}{\sigma_j^2}$$

- Modified χ^2 uses response functions
- $n_i^{test'}$ includes the response function impact on each channel
- Right: χ^2 vs f for **CC M_A^{res}**
- Gray curve represents no response (penalty term only)
- **ν_e appearance only**
- $\chi^2 = \chi^2_{\nu_e app}$

ν_e appearance only, CC M_A^{res} $(1\sigma = 20\%)$

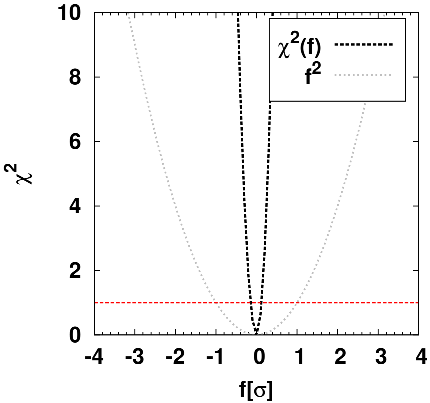


Response Functions and χ^2 (2)

$$\chi^2\left(\boldsymbol{\theta}_{true},\boldsymbol{\theta}_{test},\boldsymbol{f}\right) = 2\cdot\sum_{i}^{N_{reco}}\left(n_i^{true}\cdot\ln\frac{n_i^{true}}{n_i^{test'}}+n_i^{test'}-n_i^{true}\right)+\sum_{j}^{N_{nuis}}\frac{f_j^2}{\sigma_j^2}$$

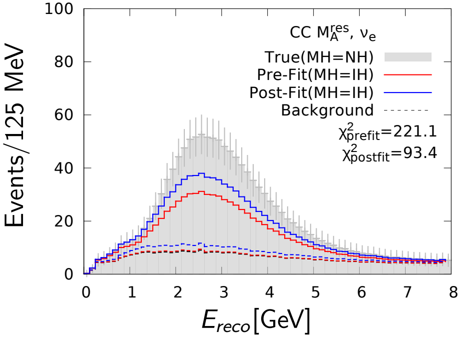
- Modified χ^2 uses response functions
- $n_i^{test'}$ includes the response function impact on each channel
- Right: χ^2 vs f for **CC M_A^{res}**
- Gray curve represents no response (penalty term only)
- **Constraint from combined fit** because f is now correlated between samples
- $\chi^2 = \chi^2_{\nu_e app} + \chi^2_{\bar{\nu}_e app} + \chi^2_{\nu_\mu dis} + \chi^2_{\bar{\nu}_\mu dis}$

Combined fit
CC M_A^{res} ($1\sigma = 20\%$)



Fit Spectra - Response Function - MH

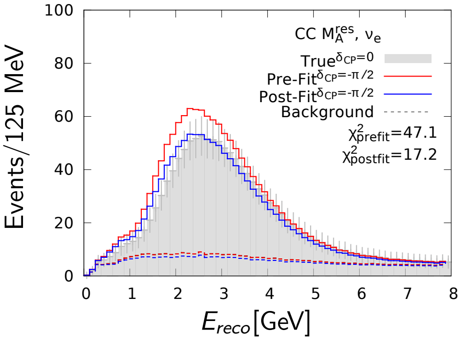
- **Fit spectra** show the effects of a systematic on the sensitivity to a particular oscillation hypothesis
- Where does the sensitivity to MH come from?
  - Compare gray area for NH to red line for IH
- How does the **CC M_A^{res}** systematic degrade the sensitivity if only ν_e appearance sample is used?
  - Compare red line for pre-fit to blue line for post-fit
- Value of CC M_A^{res} shifted by 40% (1.12 $\rightarrow$ 1.56)



- Fast MC ν_e appearance spectrum comparing the normal hierarchy to the inverted hierarchy spectra before and after including effects from CC M_A^{res}
  - $\delta_{CP} = 0$

Fit Spectra - Response Function - CP Violation

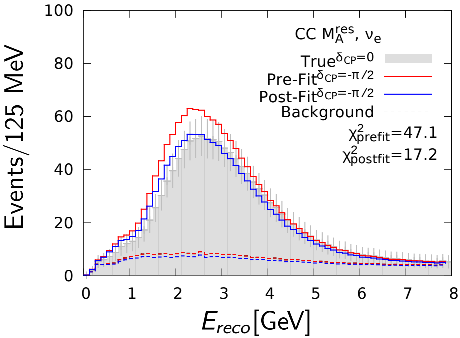
- Repeat for **CP violation** spectra
- Where does the sensitivity to CP violation come from?
  - Compare gray area for $\delta_{CP} = 0$ to red line for $\delta_{CP} = -\pi/2$
- How does the **CC M_A^{res}** systematic degrade the sensitivity if only ν_e appearance sample is used?
  - Compare red line for pre-fit to blue line for post-fit
- Value of CC M_A^{res} shifted down by $\sim$30%



- Fast MC ν_e appearance spectrum comparing the $\delta_{CP} = 0$ to the $\delta_{CP} = -\pi/2$ spectra before and after including effects from CC M_A^{res}

Fit Spectra - Response Function - CP Violation

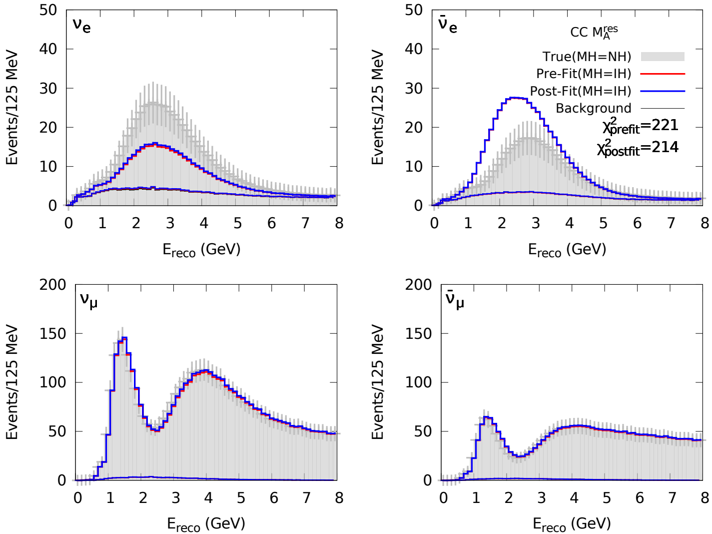
- Repeat for **CP violation** spectra
- Where does the sensitivity to CP violation come from?
  - Compare gray area for $\delta_{CP} = 0$ to red line for $\delta_{CP} = -\pi/2$
- How does the **CC M_A^{res}** systematic degrade the sensitivity if only ν_e appearance sample is used?
  - Compare red line for pre-fit to blue line for post-fit
- Value of CC M_A^{res} shifted down by $\sim$30%
- Now constrain CC M_A^{res} through a joint ν_e,$\bar{\nu}_e$ appearance + ν_μ,$\bar{\nu}_\mu$ disappearance fit



- Fast MC ν_e appearance spectrum comparing the $\delta_{CP} = 0$ to the $\delta_{CP} = -\pi/2$ spectra before and after including effects from CC M_A^{res}

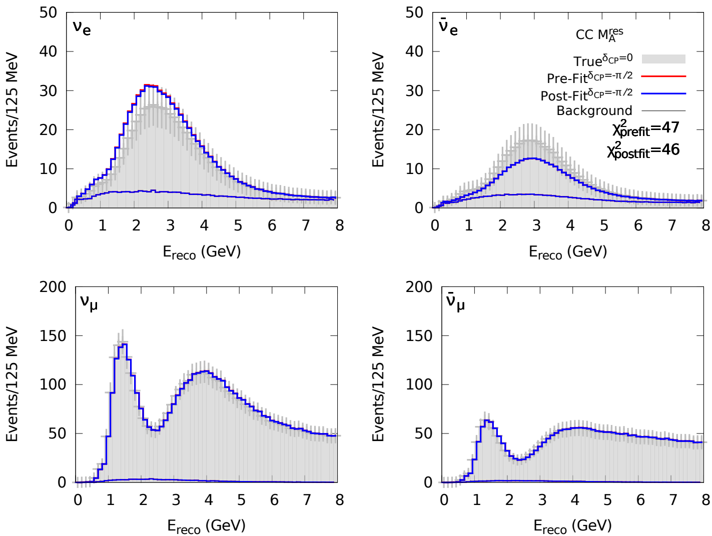
Fit Spectra - Joint Fit - MH

- Joint fit yields large constraint on CC M_A^{res} ($\sim 4\%$ or 0.2σ)
  - Infinite precision assumed on other parameters, including oscillation parameters
  - Impact will increase when all other systematics included



Fit Spectra - Joint Fit - CP Violation

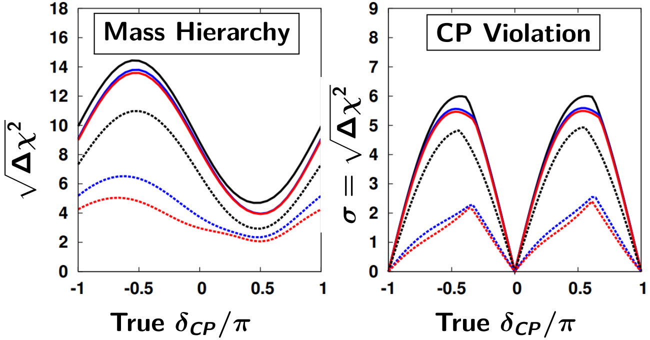
- Joint fit yields large constraint on CC M_A^{res} ($\sim 1\%$ or 0.05σ)
  - Infinite precision assumed on other parameters, including oscillation parameters
  - Impact will increase when all other systematics included



Fast MC Sensitivity

Solid:
Joint fit
245 kt.MW.yrs
Dashed:
ν_e appearance only

No systematics
Oscillation systs.
Osc. systs + CC M_A^{res}



- CC M_A^{res} uncertainty propagated to sensitivity for MH and CP violation
  - Joint fit (solid) and ν_e appearance only (dashed)
- Large effect obvious for one sample is greatly reduced for joint fit
- See **poster** by D. Cherdack on "The LBNE Fast MC"

Further Constraints

- So far have only considered constraints from far detector samples
- Other external constraints expected on
  - Hadron production from NA61/SHINE
  - Form-factors from e-N scattering
  - Cross-sections from MINERνA and MicroBooNE
  - Test beam inputs from LArIAT and CAPTAIN
- **Near detector** constraints

LBNE Near Detector

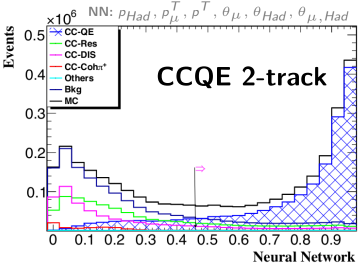
- The LBNE ND will be essential to reaching discovery-level sensitivity to CPV in LBNE
- **High resolution near detector** designed with the goal of measuring the unoscillated flux with $\leq 2\%$ precision for both shape and absolute normalization
- ND group has proposed set of physics measurements to **constrain flux** and estimated precision based on statistics at the near-site, ND simulations, and prior experience

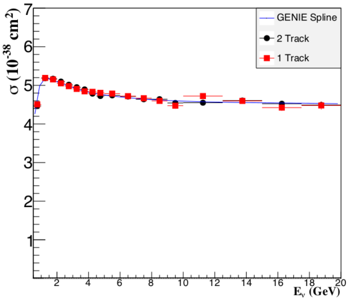
ND Flux Measurements

Leptonic	$\nu + e \rightarrow \nu + e$	$\sim$2% on absolute flux	$0.5 \leq E_\nu \leq 10$ GeV
	$\nu_\mu + e \rightarrow \nu_e + \mu$	$\sim$2.5% on absolute flux	$E_\nu \geq 11$ GeV
QE	$\bar{\nu}_\mu + p \rightarrow \mu + n$	$\sim$3% on absolute flux	$0.5 \leq E_\nu \leq 20$ GeV
Coherent	$\nu_\mu\ A \rightarrow \mu\ \rho\ A$	$\sim$5% on absolute flux	$4 \leq E_\nu \leq 20$ GeV
Low ν_0	$\nu_\mu + N \rightarrow \mu^- + X$	$\sim$1-2% on FD/ND ratio	$0.5 \leq E_\nu \leq 50$ GeV
	$\bar{\nu}_\mu + N \rightarrow \mu^+ + X$	$\sim$1-2% on FD/ND ratio	$0.5 \leq E_\nu \leq 50$ GeV

LBNE Near Detector - Simulation

- An **ND Fast MC** has been developed for baseline straw-tube tracker design
- Validated against existing NOMAD data and MC
- Example (right): extracted cross-sections for simulated 1 & 2-track **CCQE selections**
  - Evaluation of cross section measurement sensitivity
  - Propagate constraint to the FD analyses
    - Single constraint on QE events
    - In a full ND/FD combined fit
  - To do: evaluate systematic uncertainties





S. Mishra, X. Tian

Simulations - Current

- The LBNE Fast MC (beam sim. + GENIE + parameterized det. response) simulates neutrino interaction observables, and can be used to:
  - Generate near detector and far detector analysis samples
    - Reconstructed event kinematics that respect physics, det. capabilities
    - Realistic signal and background acceptances
  - Propagate systematic uncertainties event-by-event
    - Flux: beamline tolerances, physics models
    - Cross Section: model parameters, FSI
    - Detector response: calibration, energy scale
- Current studies focus on a detailed understanding of individual systematics:
  - Effects on far detector analysis spectra
  - Sensitivity degradation
  - Current and future external constraints
  - Constraints from an LBNE near detector

Simulations - Future

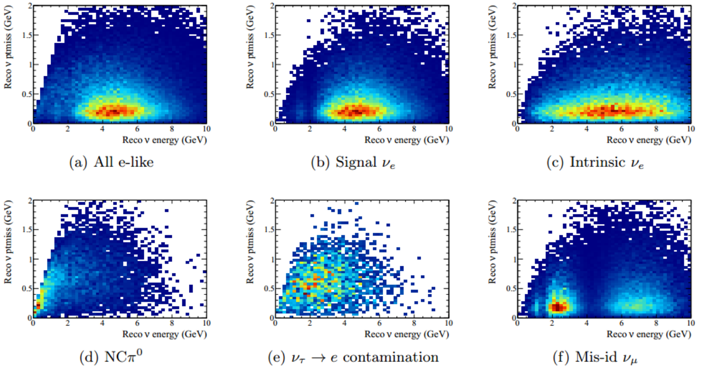
- Future studies ($\sim$6 months) will focus on:
  - Cross section ratio (ν_e/ν_μ, ν_τ/ν_μ, $\bar{\nu}/\nu$) uncertainties
  - Effect of **multiple systematics**
  - Systematic parameter **covariances**
  - Design requirements and optimizations (FD, ND, beam)
- The **VALOR** group is working on a 3-flavor analysis for LBNE, LBNO, and T2HK based on their T2K analysis
  - Developing experiment agnostic software tools
  - Simulate near detector samples, analyze, produce covariance matrix
  - Simulate far detector samples, fit for oscillation parameters, and constrain systematics with covariance matrix

Summary

- **Constraining systematics** is essential to **discovery** of CP violation and determining the mass hierarchy
- **Shape** information is crucial and further studies that introduce realistic shape uncertainties are underway
- LBNE and LBNO both developing detailed **simulations** to study effects of neutrino interaction, flux, and detector systematics
- The **LBNE Fast MC** simulation effort has started to produce results estimating impact of individual systematics

Backup slides

LBNO - Event Distributions

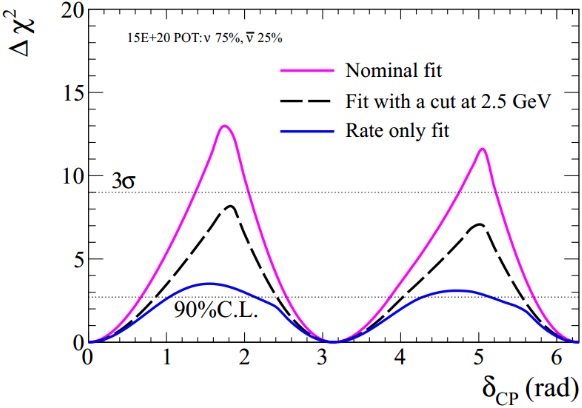


Agarwalla et al, arXiv:1312.6520v3

- Event distributions for channels that contribute to the ν_e appearance sample
- $\delta_{CP} = 0$, Normal Hierarchy

LBNO - Rate Only and 2nd Osc. Max.

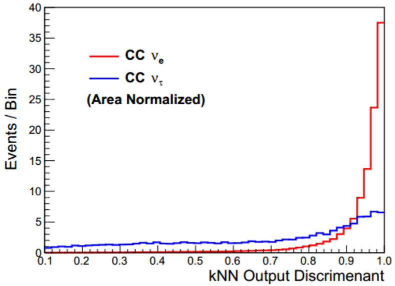
- Rate only leads to drastic loss in CP violation sensitivity
- Covering multiple oscillation maxima contributes greatly to sensitivity

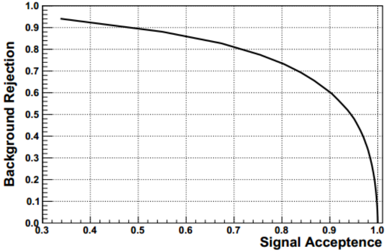


Agarwalla et al, arXiv:1312.6520v3

LBNE - ν_τ Reduction

- LBNE Fast MC uses a preliminary algorithm for removing ν_τ CC induced backgrounds from the ν_e appearance and ν_μ disappearance samples
- k-Nearest-Neighbors (kNN) ML technique from ROOT TMVA is used
- kNN inputs are: sum of transverse momentum wrt incoming ν direction, E_{reco}, reconstructed E_{had}





LBNE ND - Reference Design

- Reference design is a fine-grained tracker consisting of a straw-tube tracker and ECAL inside of a 0.4-T dipole magnet

FGT Parameters

Parameter	Value
STT detector volume	$3 \times 3 \times 7.04$ m^3
STT detector mass	8 tons
Number of straws in STT	123,904
Inner magnetic volume	$4.5 \times 4.5 \times 8.0$ m^3
Targets	1.27-cm thick argon ($\sim$ 50 kg), water and others
Transition radiation radiators	2.5 cm thick
ECAL X_0	10 barrel, 10 backward, 18 forward
Number of scintillator bars in ECAL	32,320
Dipole magnet	2.4-MW power; 60-cm steel thickness
Magnetic field and uniformity	0.4 T; $<2\%$ variation over inner volume
MuID configuration	32 RPC planes interspersed between 20-cm thick layers of steel

FGT Performance

Performance Metric	Value
Vertex resolution	0.1 mm
Angular resolution	2 mrad
E_e resolution	5%
E_μ resolution	5%
$\nu_\mu/\overline{\nu}_\mu$ ID	Yes
$\nu_e/\overline{\nu}_e$ ID	Yes
NCπ^0/CCe rejection	0.1%
NCγ/CCe rejection	0.2%
NCμ/CCe rejection	0.01%

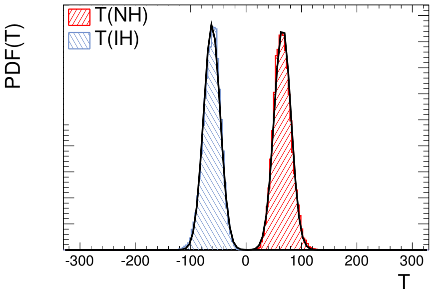
VALOR

- VALOR (C.Andreopoulos et al.) is a T2K oscillation fitting group
  - Well-established with contributions to many published T2K oscillation results.
  - Contributions from Liverpool, STFC/RAL, ETHZ, Oxford, Warwick, IFIC Valencia and Lancaster.
  - A full 3-flavor oscillation analysis framework that can also accommodate sterile neutrino models (3+1, 3+2).
  - Implements an indirect extrapolation method, with a flux and systematic constraint from a high-granularity ND.
- Software already adapted for T2HK:
  - Same beamline, ND and FD technology
  - Effort to include simulations for additional WC ND detector at 2km
- Further adaptation to include LBNE and LBNO is nearly complete:
  - Initial effort to derive flux and cross-section systematic constraints
    - Joint fit of the (E_{reco},y_{reco}) distributions
    - Inclusion of several near detector semi-inclusive samples, including: ν_μ CC 1-track and 2-track QE-like, ν_μ CC $1\pi^+$, ν_μ CC $1\pi^0$, NC $1\pi^0$, ν_e CC
- Objectives:
  - Oscillation sensitivities for T2HK, LBNE, and LBNE using common physics assumptions.
  - Physics-driven requirements for the near detector designs of all 3 experiments

Statistics Detail for MH and CPV

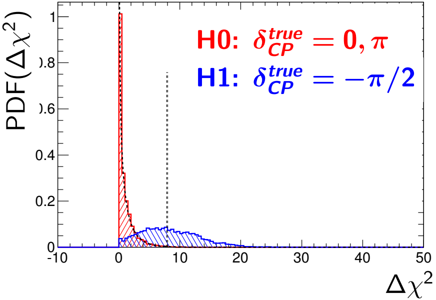
- If Poisson statistical effects are included using Toy MC throws:

Mass Hierarchy Statistic



- $\Delta\chi^2_{NH} = \chi^2(NH, IH) - \chi^2(NH, NH)$
- Not a χ^2 distribution for 1 dof
- e.g. $\overline{\Delta\chi^2} = 36$, $\alpha = \beta$ means 0.13% probability of ruling out true MH and of accepting wrong MH

CP Violation Statistic



- $\Delta\chi^2 = \mathrm{Min}[\chi^2(\delta_{CP}^{true}, \delta_{CP}^{test} = 0), \chi^2(\delta_{CP}^{true}, \delta_{CP}^{test} = \pi)]$
- Wilk's theorem applies and this is asymptotically χ^2 distributed (1 dof): $\sqrt{\Delta\chi^2} \approx \sigma$

Systematics for T2HK

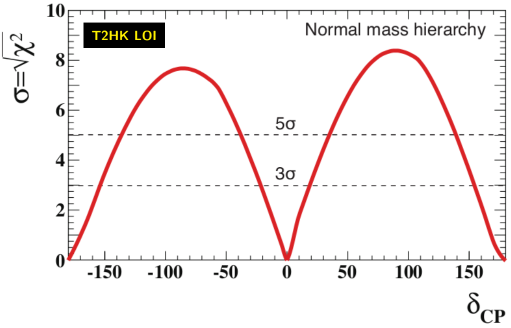
$$\chi^2\left(\boldsymbol{\theta}_{true},\boldsymbol{\theta}_{test},\boldsymbol{f}\right)=2\cdot\sum_{i}^{N_{reco}}\left(n_i^{true}\cdot\ln\frac{n_i^{true}}{n_i^{test'}}+n_i^{test'}-n_i^{true}\right)+\sum_{i,j}^{N_{bins}}f_i(C^{-1})_{i,j}f_j$$

- **T2HK**
  - Uses normalized covariance matrix, C, to constrain per-bin systematic nuisance parameters f_i
  - Assuming the T2K neutrino beamline and near detectors and takes into account improvements expected from future running in T2K

T2HK LOI

Source	ν mode		$\overline{\nu}$ mode	
	Appearance	Disappearance	Appearance	Disappearance
Flux & ND-constrained cross section	3.0	2.8	5.6	4.2
ND-independent cross section	1.2	1.5	2.0	1.4
Far detector	0.7	1.0	1.7	1.1
Total	3.3	3.3	6.2	4.5

T2HK Sensitivity



- CP violation detected at greater than 5σ for 58% of δ_{CP} values
  - 1:3 ν:$\bar{\nu}$