LONG-BASELINE OSCILLATION PHYSICS IN DUNE

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Neutrino – Latin America Workshop

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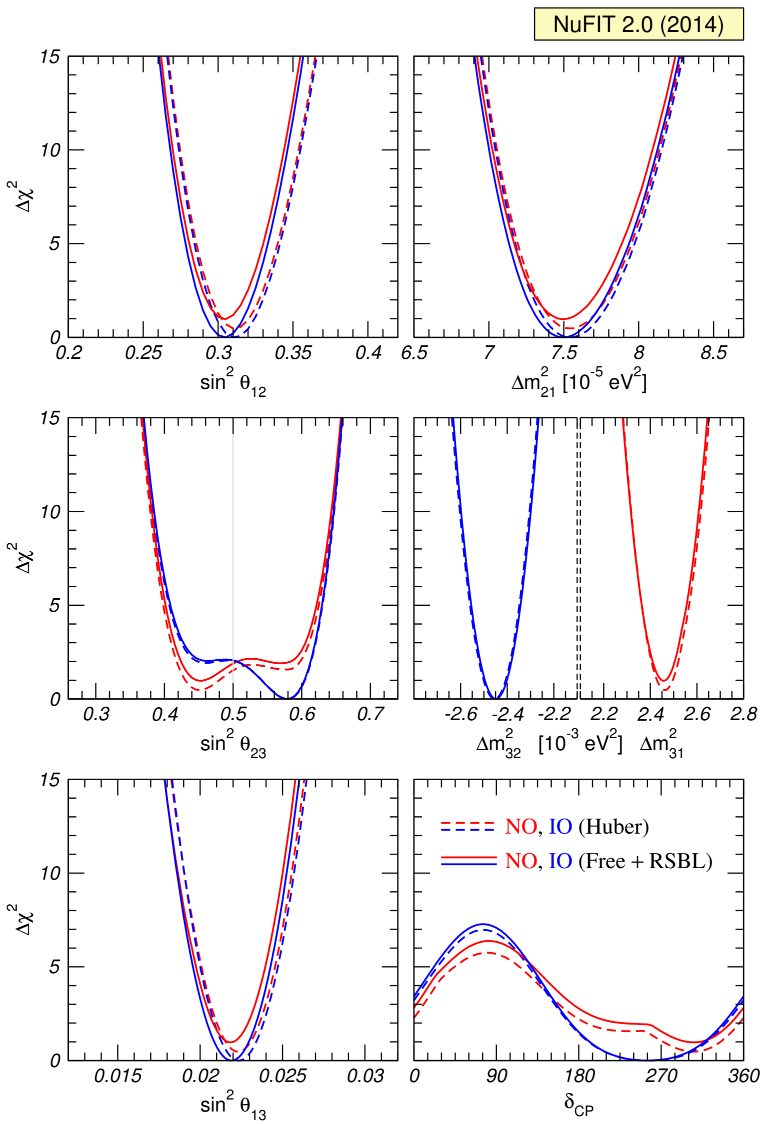
Overview

- Introduction to long-baseline neutrino oscillation
- Oscillation sensitivity in DUNE
- Systematic uncertainties
- Additional physics topics

Oscillation Parameters



- NuFit 2014
  - http://www.nu-fit.org/
  - Includes results through NOW 2014
  - θ_{13}, θ_{12}, Δm^2_{21}, $|\Delta m^2_{32}|$ each known to a few percent
  - θ_{23} known to ~6% (octant unknown)
  - Some preference for $\delta_{CP} < 0$
- Further constraints expected from existing and planned experiments:
  - Hints from T2K and NOvA suggest $\delta_{CP} < 0$
  - External constraints on mixing angles improve early sensitivity
  - Measurements or hints of MH or δ_{CP} value could influence run plans
- Ultimate DUNE goals include precise measurements of θ_{13}, θ_{23}, Δm^2_{32}, and δ_{CP} for unitarity and sum rule tests

ν_e Appearance

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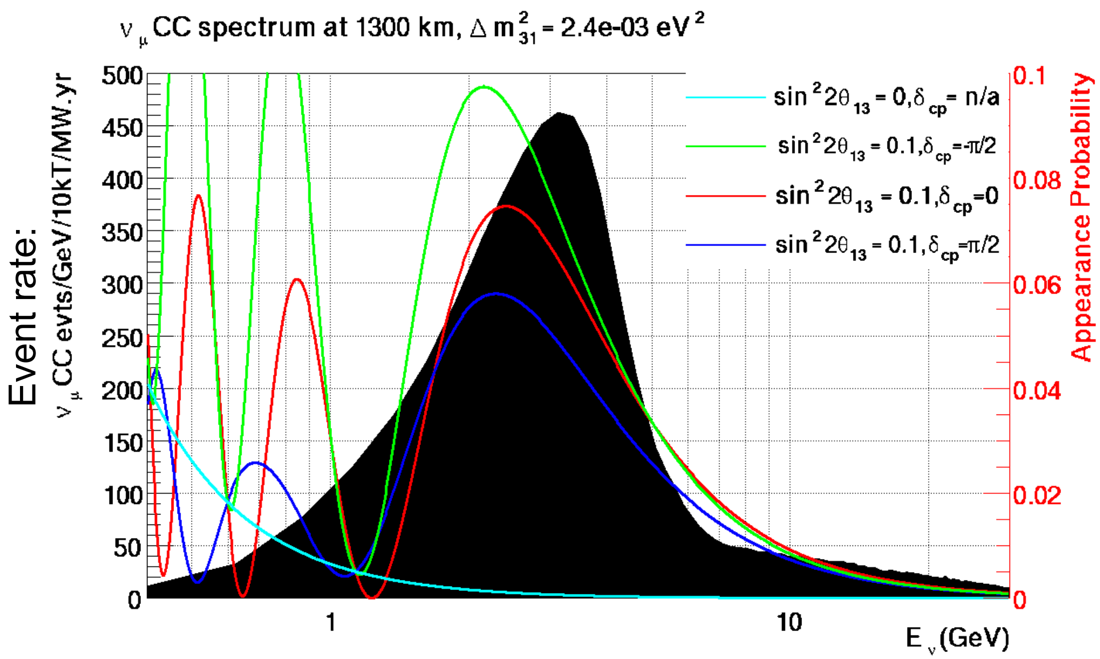
$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2 +$$
$$\alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} -$$
$$\alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

$$a = G_F N_e \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



- ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects – measurements of all four possible in a single experiment
- Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample

Matter and CP Asymmetry

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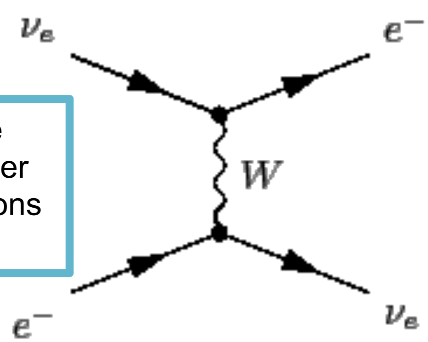
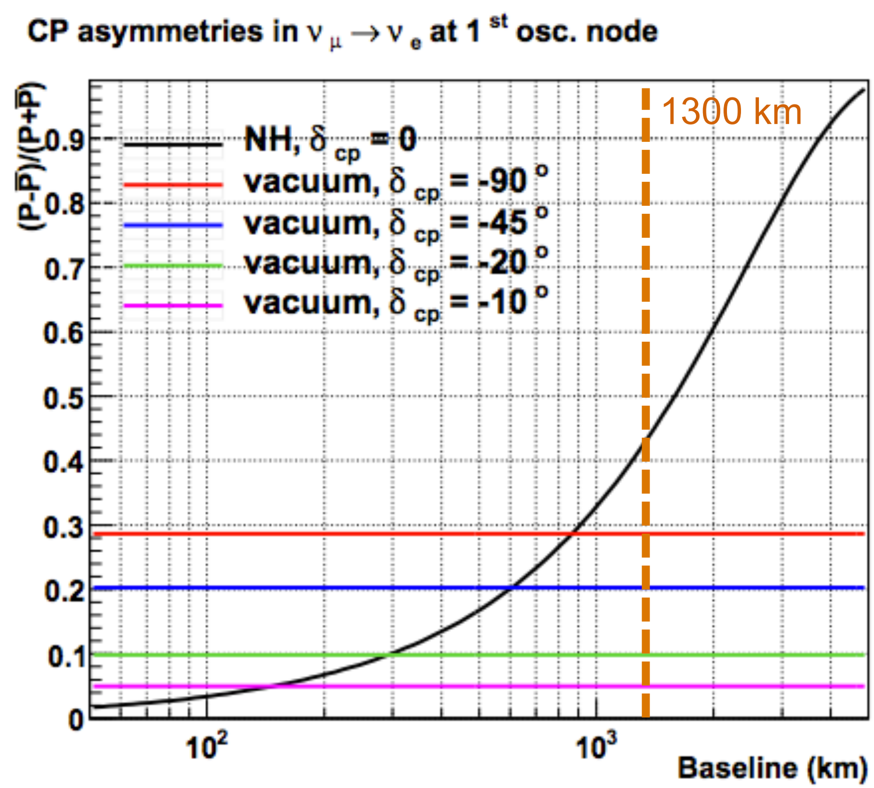
Charged-current coherent forward scattering on electrons:

Electrons are present in matter while other leptons are not.

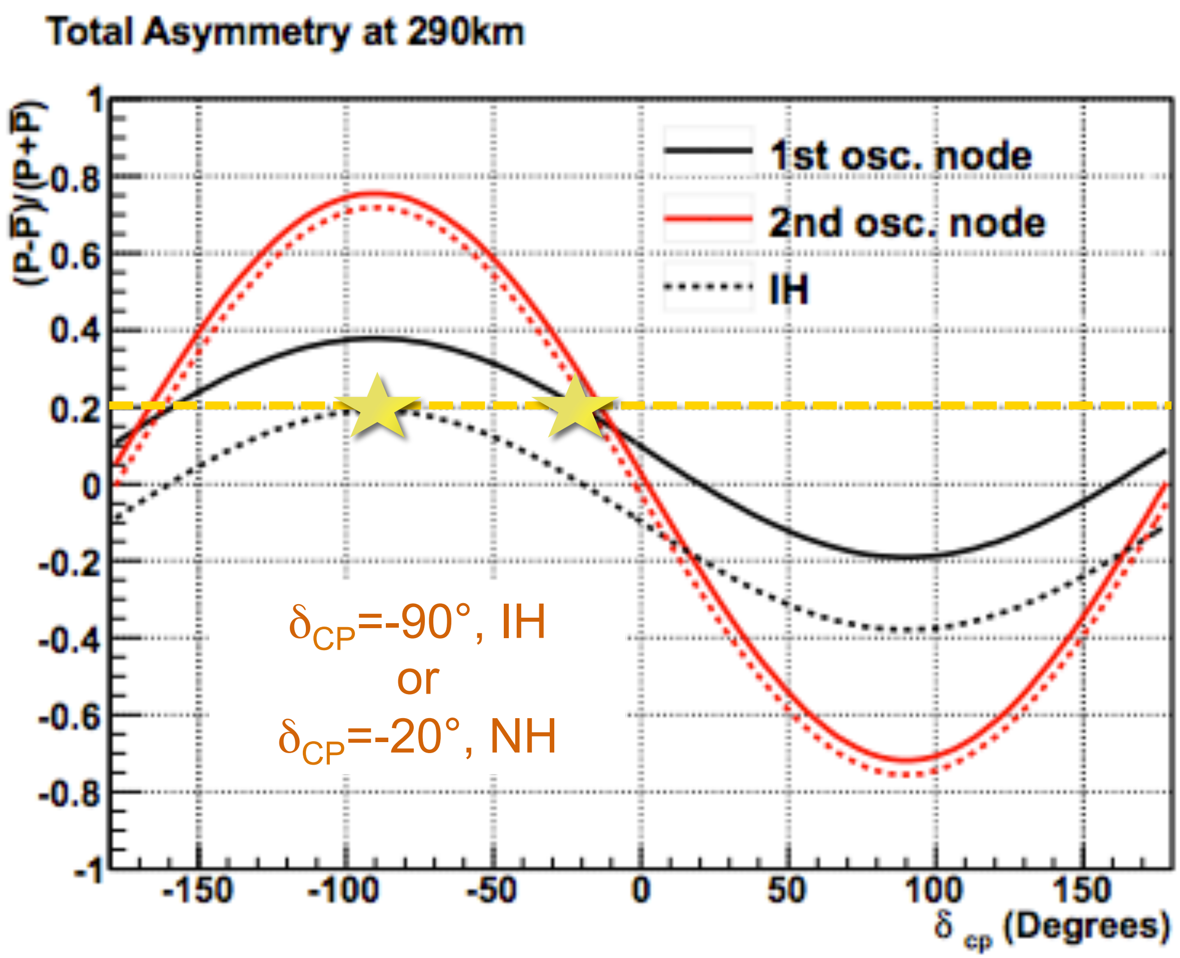




- CC process occurs for electron neutrinos only; muon and tau have only NC interactions with electrons
- Normal hierarchy: matter effect enhances appearance probability for neutrinos and suppresses it for antineutrinos (opposite for IH)

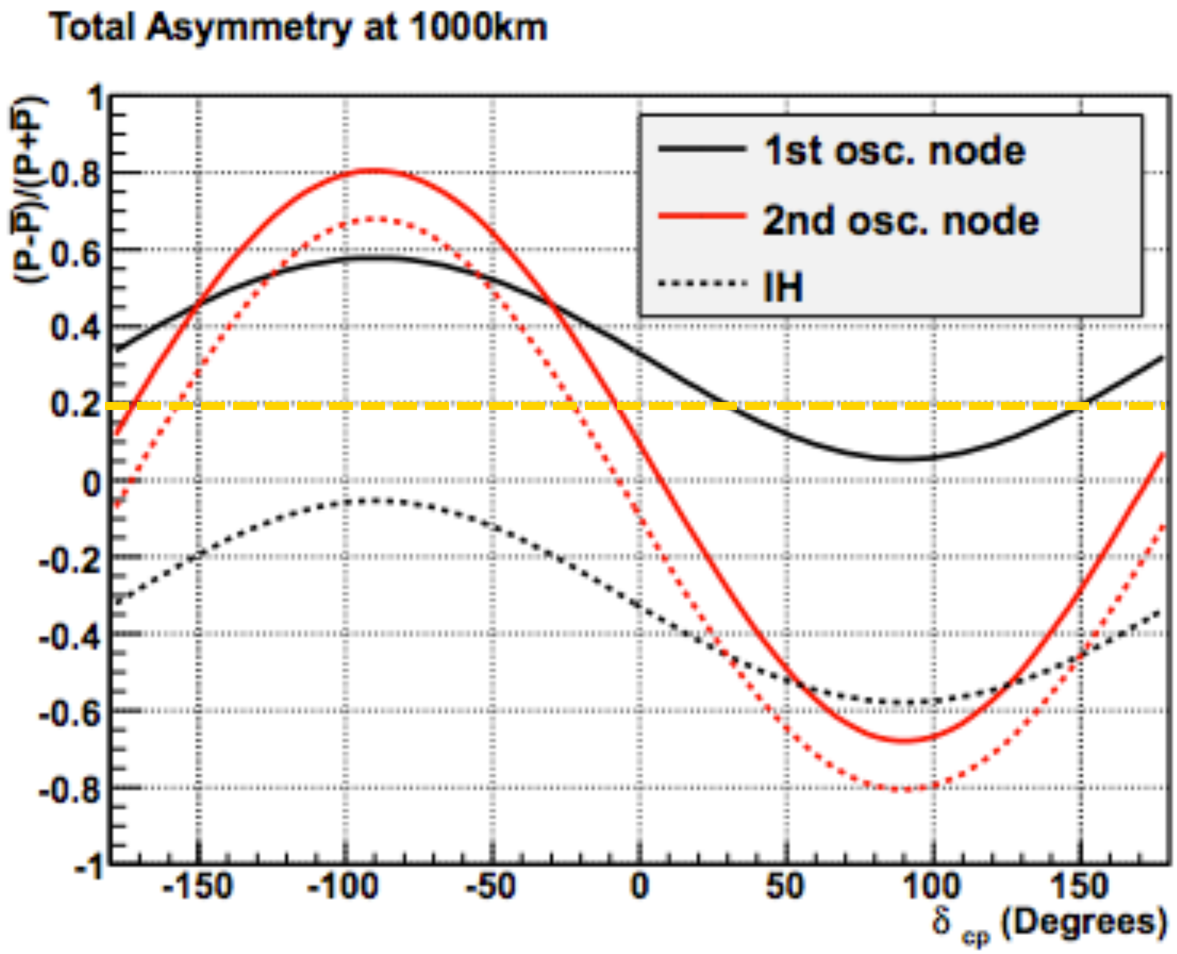
Matter asymmetry very important for long-baseline experiments!

Matter and CP Asymmetry



Degeneracy between CP and matter asymmetry for 1st oscillation node at short baseline

Matter and CP Asymmetry



Longer baseline breaks degeneracy between CP and matter asymmetry

DUNE

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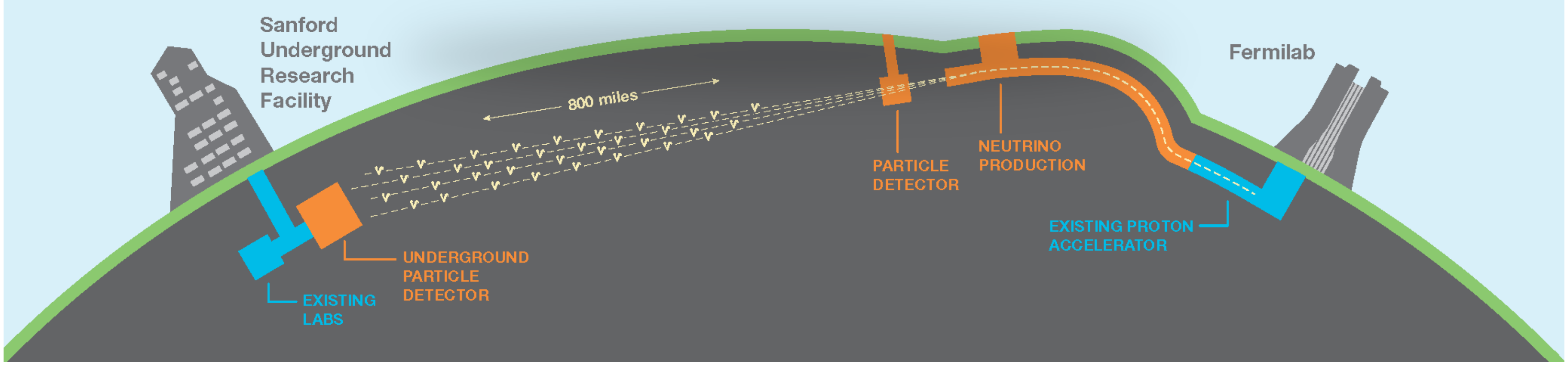
Measure ν_e appearance and ν_μ disappearance in a wideband neutrino beam at 1300 km to measure MH, CPV, and neutrino mixing parameters in a single experiment.



Signal Efficiency

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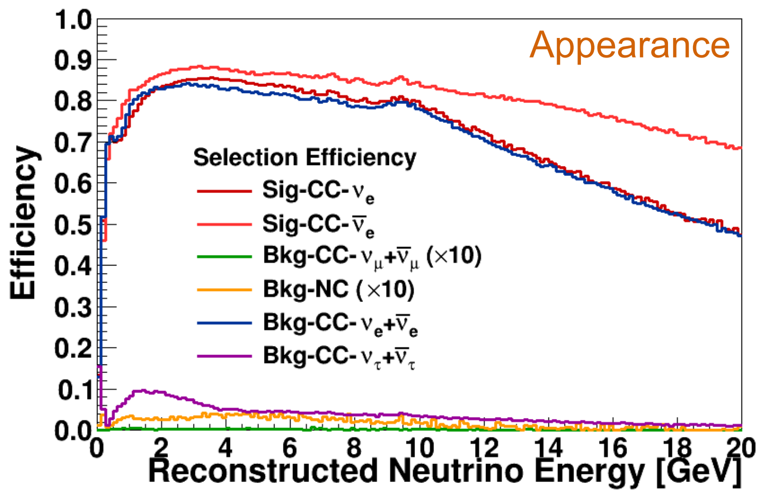
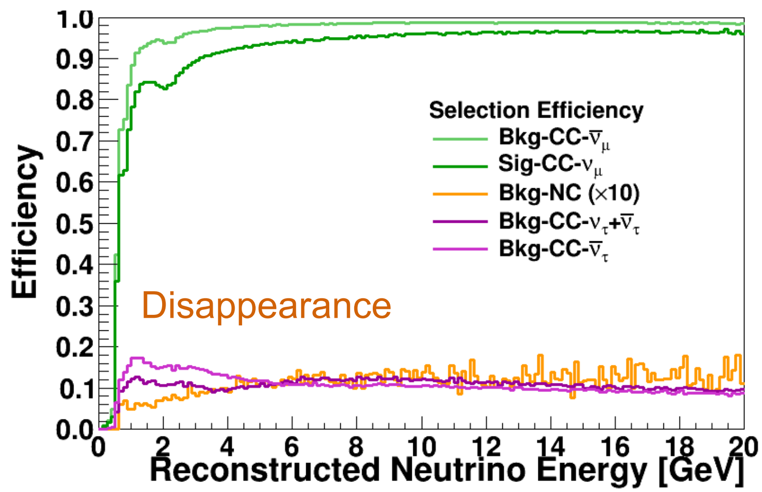
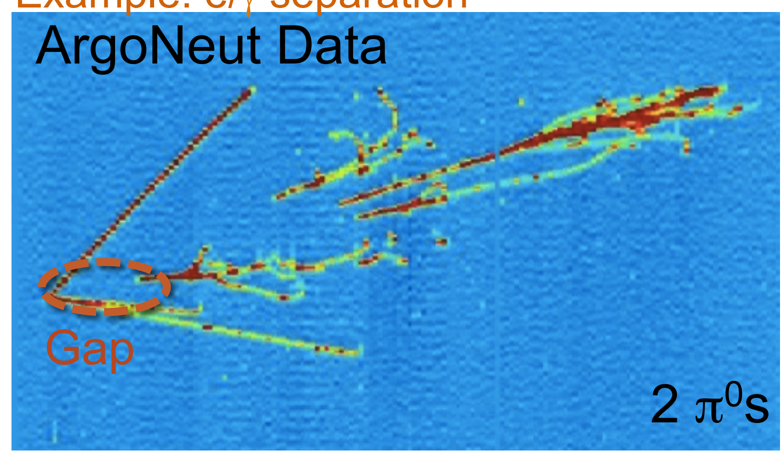
DUNE CDR:





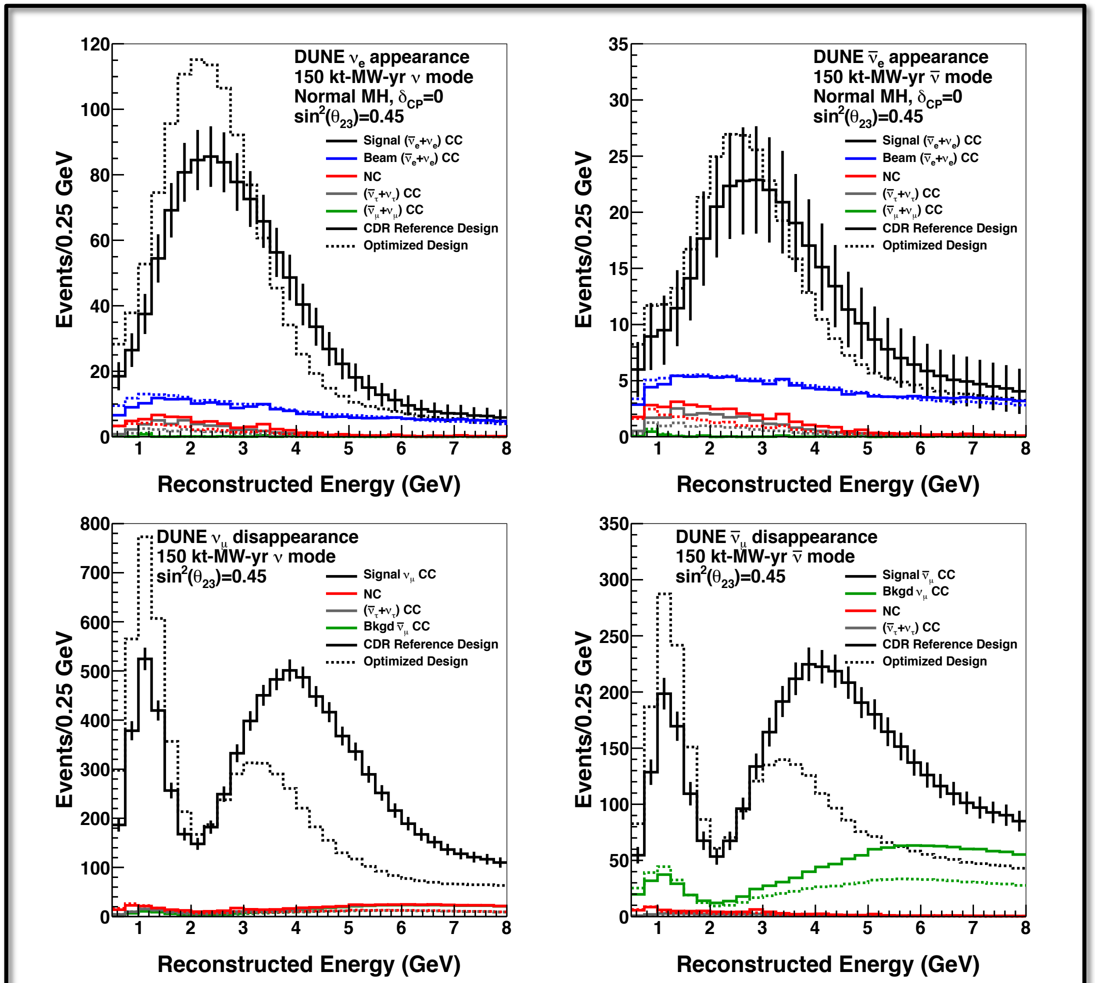
- Expected efficiency from analysis of parameterized Fast MC
  - Detector performance parameters based on previous experiments and simulations
  - Reconstruction/analysis efforts underway to demonstrate performance with DUNE simulation
- Current generation of experiments have much to contribute to understanding of reconstruction/analysis in LArTPCs

Example: e/γ separation



Sensitivity Calculations

DUNE CDR:

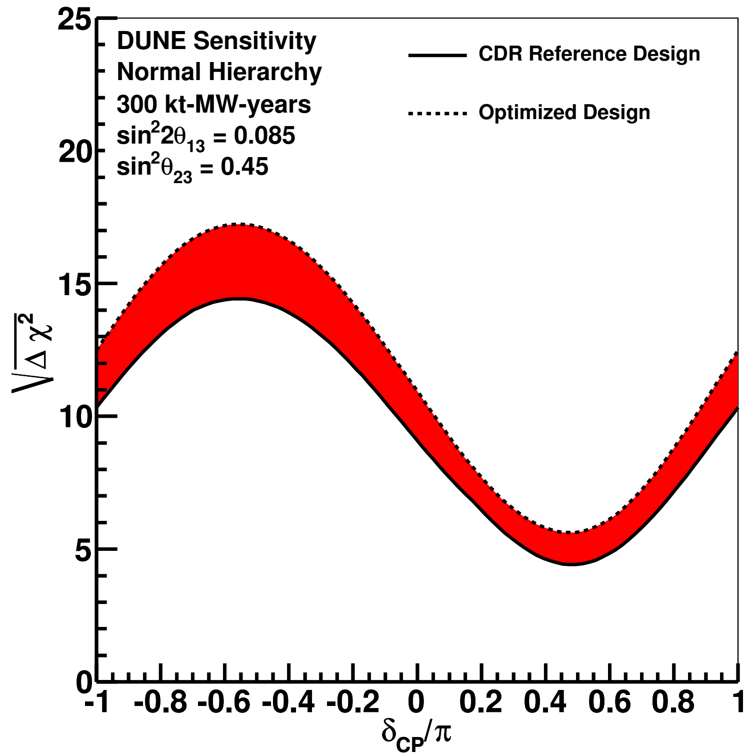


- GLoBES-based fit to four FD samples
- Two neutrino beam line designs considered
- GENIE event generator
- Reconstructed spectra predicted using detector response parameterized at the single particle level
- Simple systematics treatment
- GLoBES configurations to be made public soon

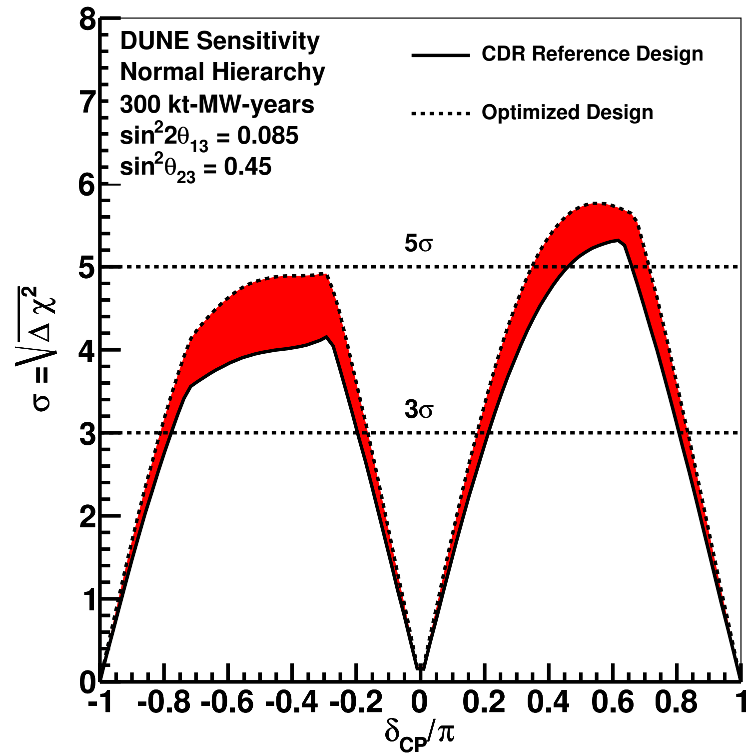
DUNE Sensitivity

DUNE CDR:

Mass Hierarchy



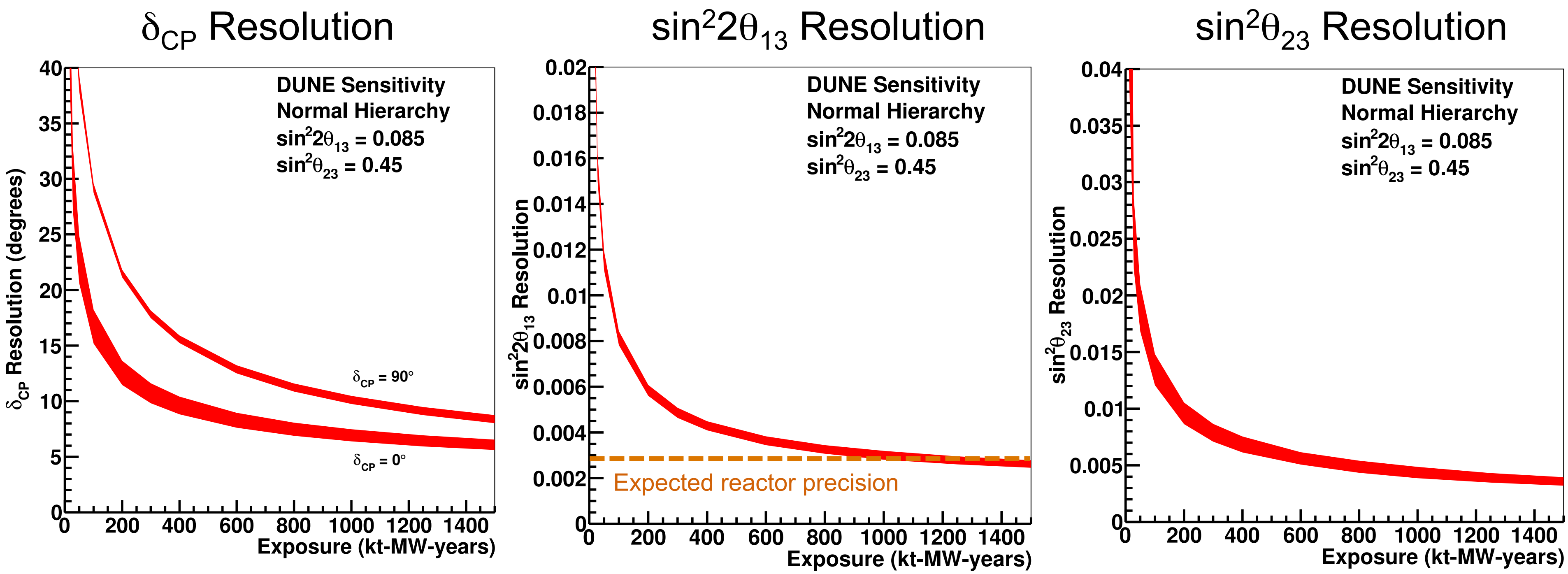
CP Violation



Width of band indicates variation among differing neutrino beam designs.
Exposure is 300 kt.MW.yr = 40 kt x 1.07 MW x ($3.5\nu+3.5\bar{\nu}$) years.
Includes simple normalization systematics and oscillation parameter variations.

Oscillation Parameter Sensitivity

DUNE CDR:



DUNE Sensitivity Over Time

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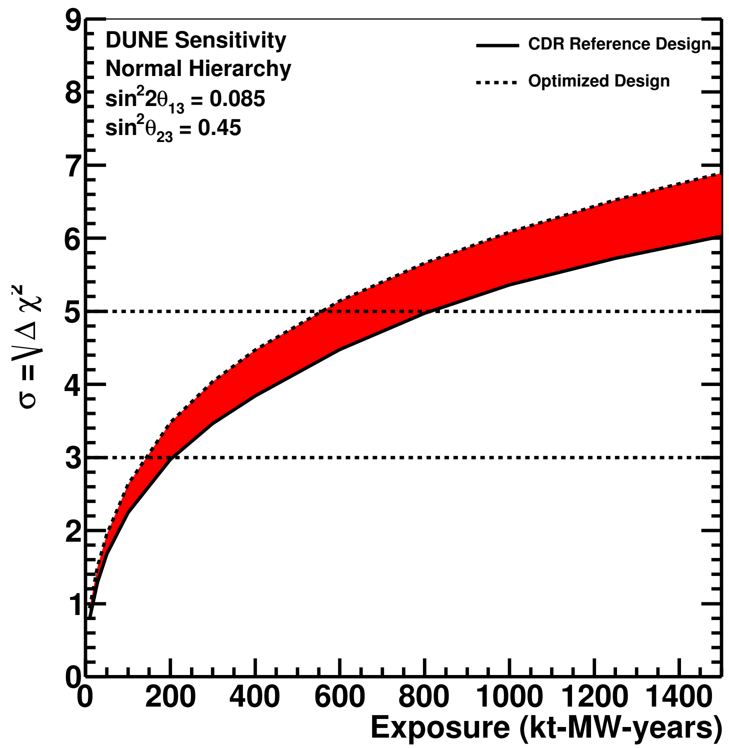
DUNE CDR:

Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{\rm CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\rm CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{\rm CP} = 0$)	450	290
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	525	320
CPV at 5σ 50% of $\delta_{\rm CP}$	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of $\delta_{\rm CP}$	1320	850

Interesting measurements will be made throughout the DUNE physics program!

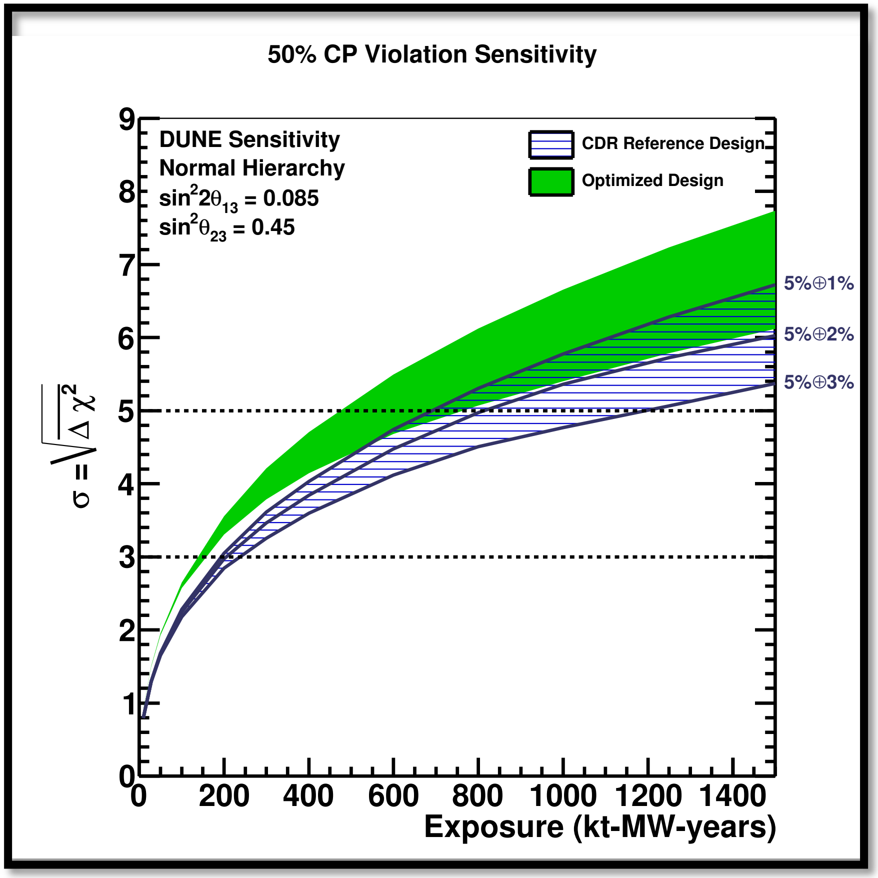
CP Violation



Initial beam power: 1.07 MW at 80 GeV
Planned upgrade to > 2 MW

Systematic Uncertainty

DUNE CDR:



- 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.
  - $\nu_\mu = \bar{\nu}_\mu = 5\%$
  - $\nu_e = \bar{\nu}_e = 2\%$
- Uncertainty in ν_e appearance sample normalization must be ~5% ⊕ 2% to discover CPV in a timely manner.

Sources of 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.

Strategy for Flux

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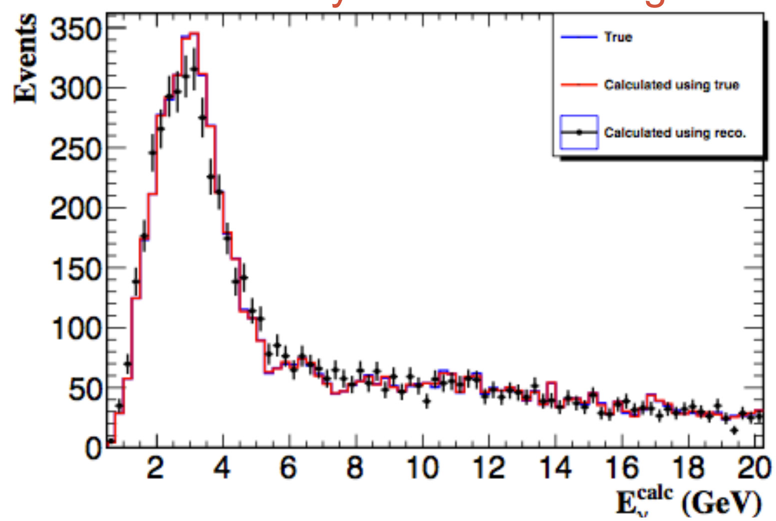
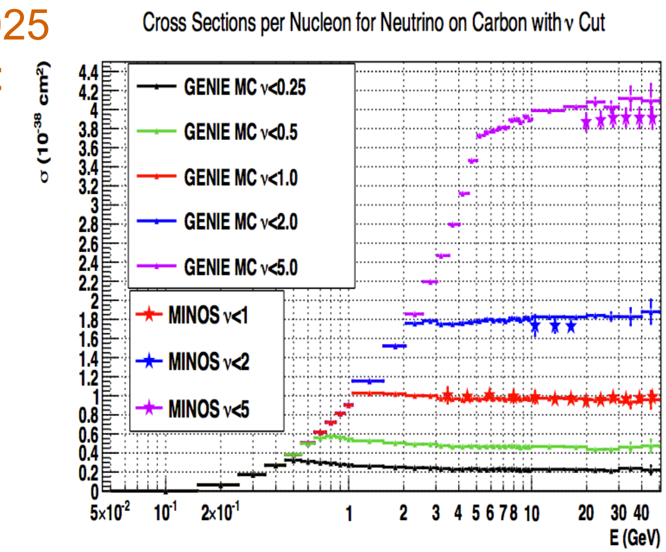
- Constrain absolute flux with near detector measurements of fully-leptonic neutrino interactions
  - Cross-sections known to high precision
  - Neutrino-electron scattering: ~3% stat. (E_ν < 5 GeV)
  - Inverse muon decay: ~3% stat. (E_ν > 11 GeV)
- Constrain flux shape using low-ν_0 method: 1-2%
- Low-ν_0 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:



120 events in MINERvA → 13% constraint on NuMI flux, statistically limited (J. Park thesis)

arXiv:1201.3025 (Bodek et al.):



Strategy for Interaction Model

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

Improving Interaction Models

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- Worldwide effort that will benefit DUNE!
- Alternative models being implemented in GENIE include:
  - 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
- Comparisons among generators
- Neutrino interaction data available or coming soon from:
  - ArgoNeuT, MINERvA, CAPTAIN-MINERvA, NOvA-ND, T2K-ND280, μBooNE, SBND, ICARUS, …
- Electron-argon scattering data coming soon from JLab

DUNE collaborators active in all of these efforts!

Constraints on Cross-Section Ratios

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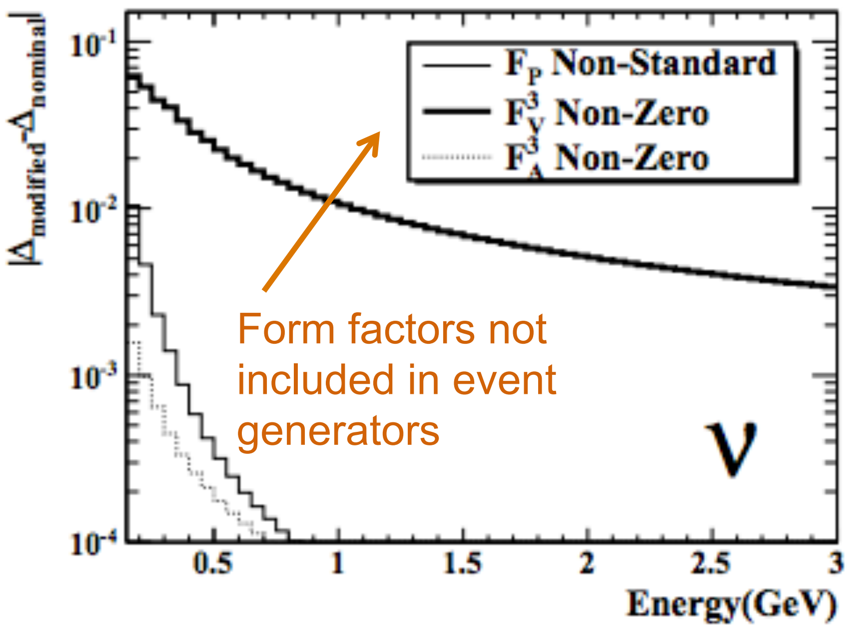
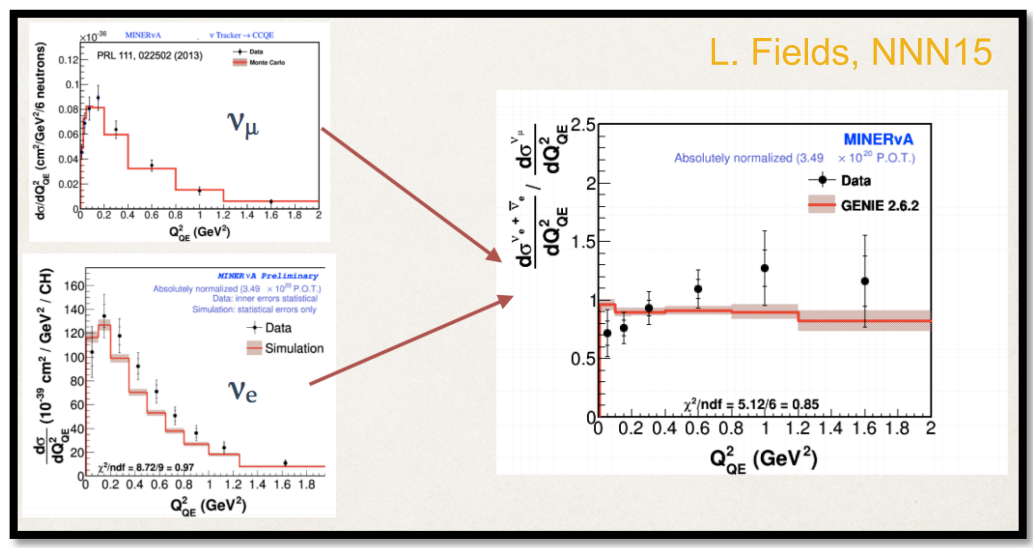
- Theoretical and experimental constraints on variation in $\nu/\bar{\nu}$ and ν_e/ν_μ cross-section ratios determines how much four far-detector samples can constrain uncertainty from cross-section models
  - Current nominal variation for DUNE studies is 10% for $\nu/\bar{\nu}$ and 2.5% for ν_e/ν_μ
  - Even a consensus on the right order of magnitude for these uncertainties would be valuable

arXiv:1206.6745



MINERvA CCQE
arXiv:1509.05729



Strategy for 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
  - Experience from Intermediate Neutrino Program LArTPCs expected to inform simulation, reconstruction, and calibration of DUNE's far detector
- Calibration program
  - LArIAT, CAPTAIN, DUNE 35-ton prototype, protoDUNEs
- Improved neutrino interaction model will reduce impact of imperfect reconstruction of neutrons and low-energy protons on analysis

DUNE 35-ton APAs:

Additional Physics Topics

DUNE
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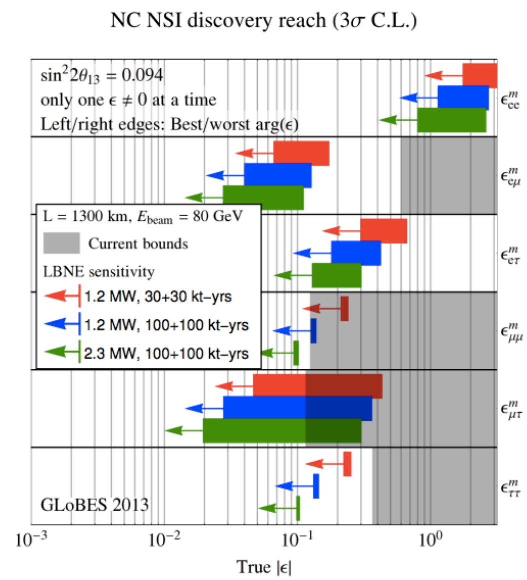
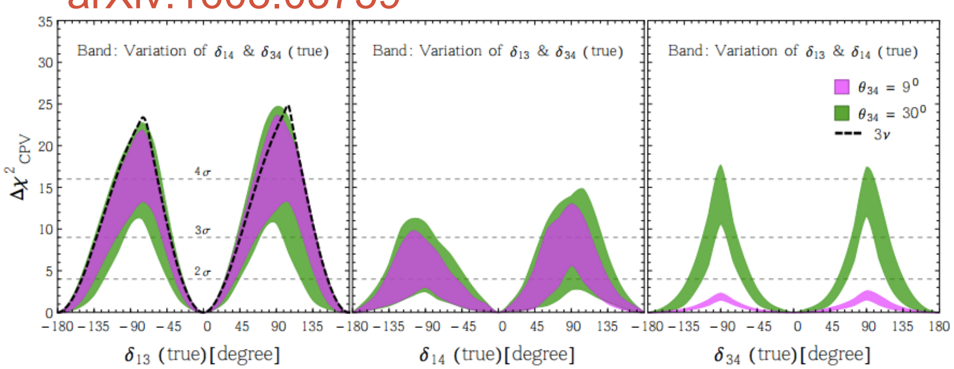
- ν_τ appearance
  - Expect >100 events per year at far detector (dependent on flux)
  - Higher energy tune would produce larger samples
- New physics affecting long-baseline oscillation
  - NSI
  - Long-range interactions
  - Large extra dimensions
  - Lorentz/CPT violation
  - Mixing with sterile ν
- Phenomenology
  - Sum rules; impact of CP violation; quantification of goals for precision parameter measurements

Individual effort could make huge impact on any of these topics!

arXiv:1307.7335



arXiv:1603.03759



Summary

- DUNE will be sensitive to neutrino mass hierarchy, CP violation, and precision measurements of oscillation parameters θ_{13}, θ_{23}, Δm^2_{32}, and δ_{CP} in a single experiment.
- DUNE will be sensitive to new physics.
- DUNE will make interesting physics measurements at every phase of experimental operations.
- Reconstruction and event selection are critical.
  - Still work in progress
- Constraint of systematic uncertainty is critical.
  - Still work in progress
  - Existing and near-future experiments are making many measurements needed to constrain DUNE systematics
- Theory/Phenomenology input is critical.
  - Improving/understanding neutrino interaction models
  - Understanding impact of precision measurements