Prospects for Precision Measurements at DUNE

Jeremy Fleishhacker and Chris Marshall
University of Rochester
8 August, 2022

What's New About This Study?

- More carefully handles parameter correlations and degeneracies than previous studies
- Reports parameter-dependent resolutions and multi-dimensional allowed regions for a wide range of true parameters
- More studies without the reactor θ_{13} constraint
- Sensitivity to tension with reactor measurement

Pseudoexperiment “Throw” Studies

True Point 1

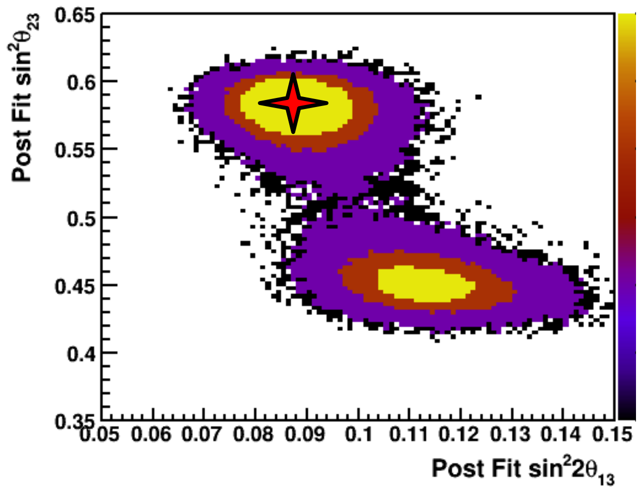
Parameter	Value
$\sin^2 2\theta_{13}$	0.88
Δm^2_{32}	2.45×10^{-3} eV^2
$\sin^2\theta_{23}$	0.58
δ_{cp}	-0.25π

True Point 2

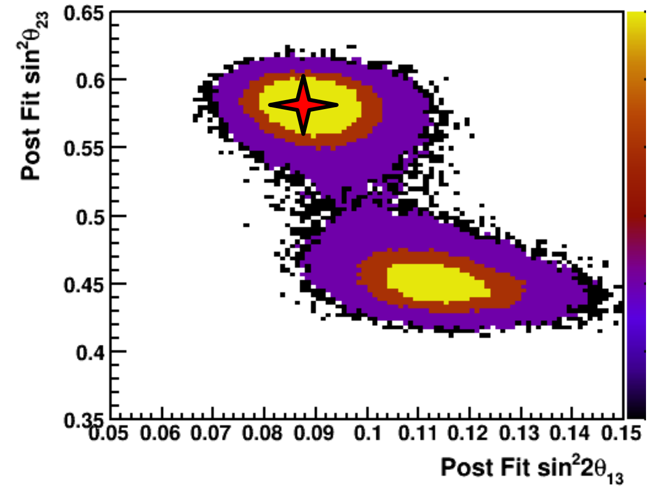
Parameter	Value
$\sin^2 2\theta_{13}$	0.88
Δm^2_{32}	2.45×10^{-3} eV^2
$\sin^2\theta_{23}$	0.58
δ_{cp}	-0.5π

- Many pseudoexperiments simulated, true systematics randomly varied
- Two true points, simulated at 100 and 1000 ktMWyrs

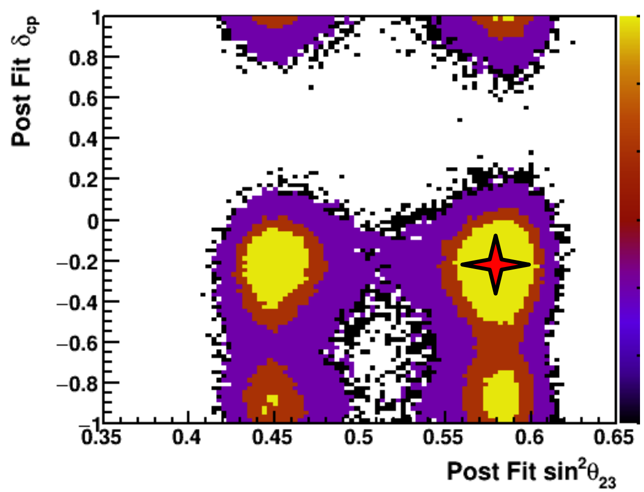
Precision Measurement Capabilities: 100ktMWyr Exposure

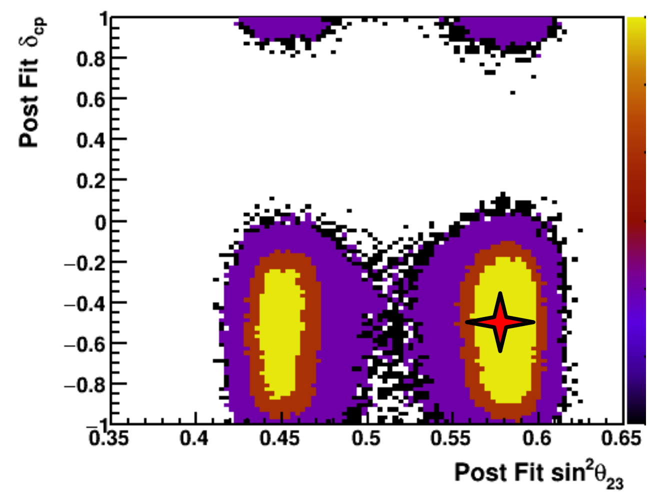


True Point 1

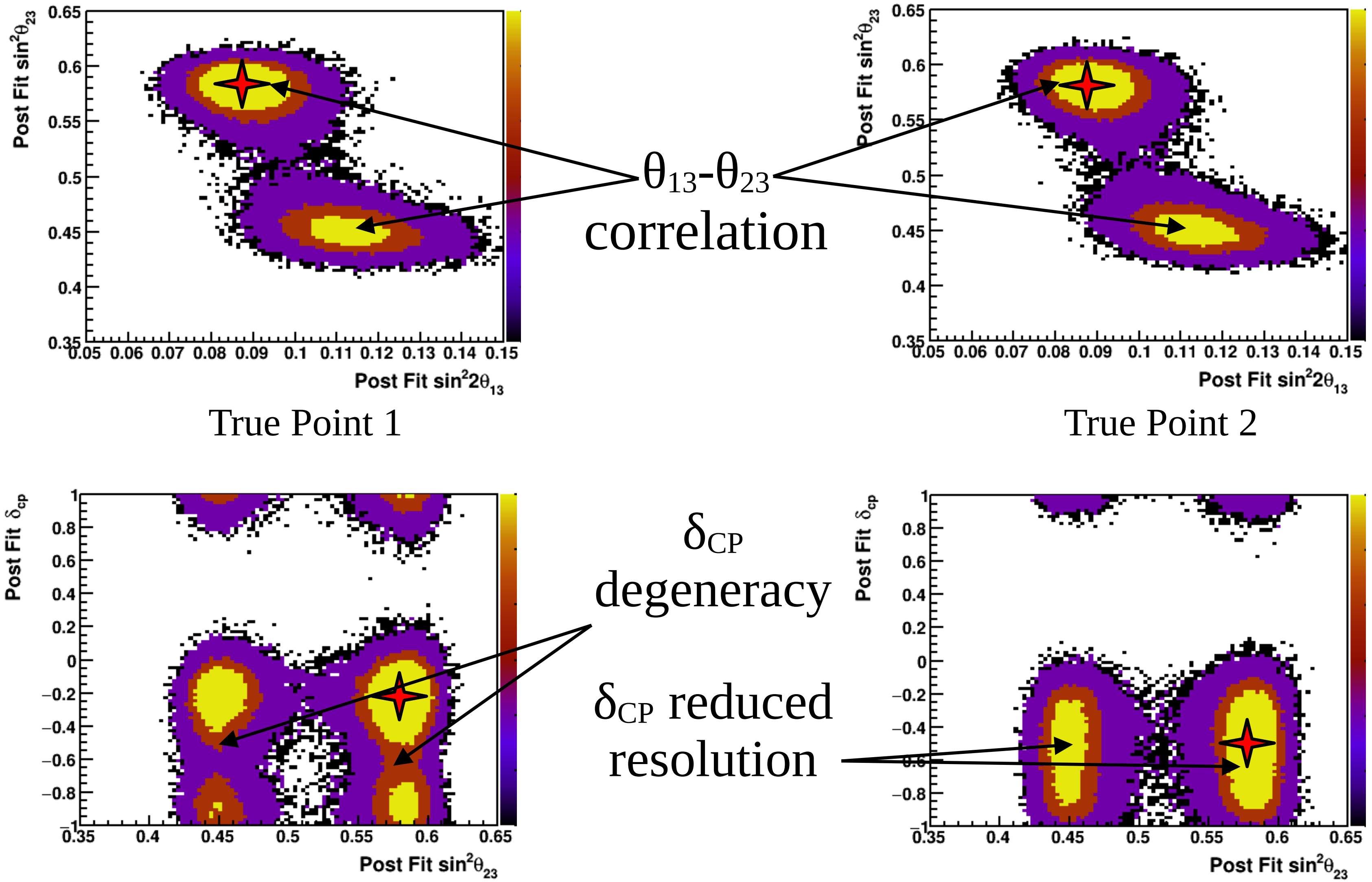


True Point 2

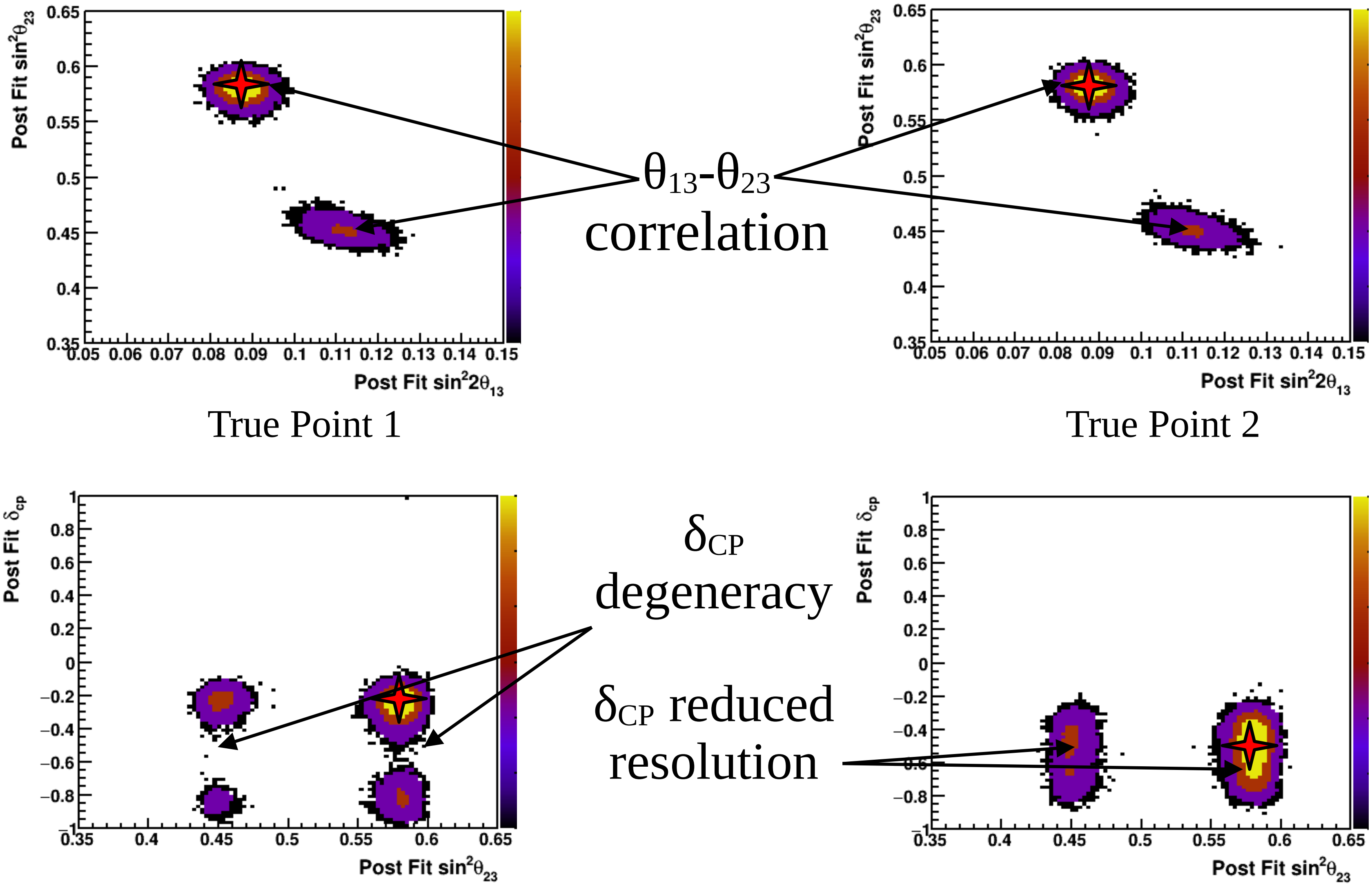




Precision Measurement Capabilities: 100ktMWyr Exposure



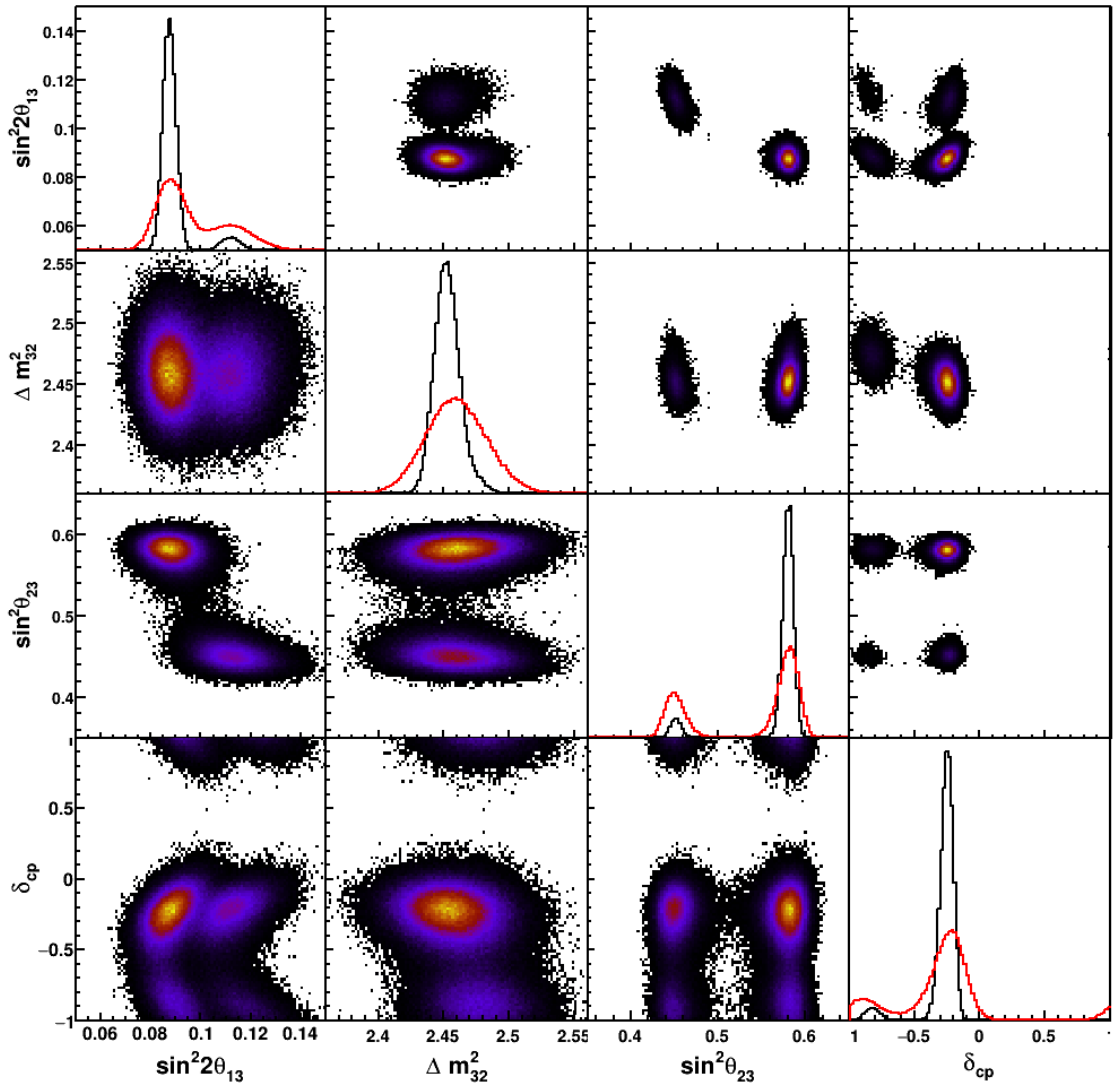
Precision Measurement Capabilities: 1000ktMWyr Exposure



True Point 1

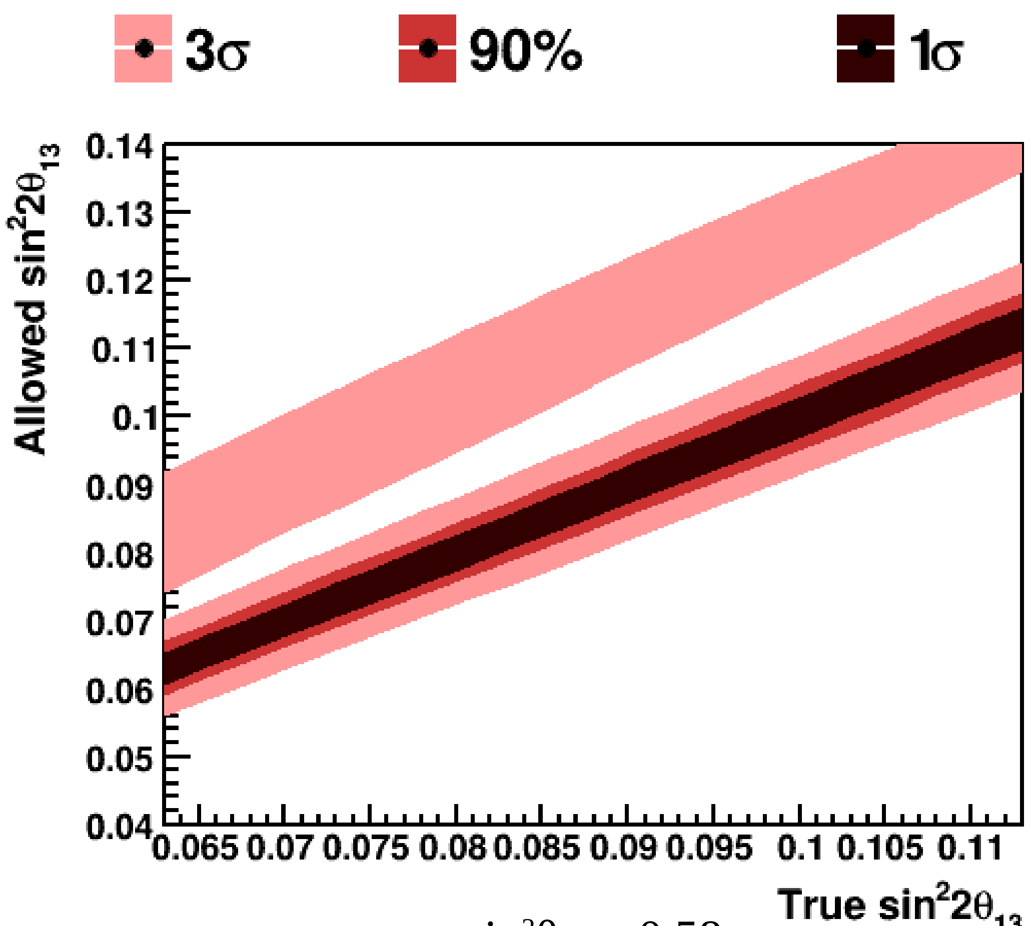
True Point 2

True Point 1: Full 4D Parameter Space

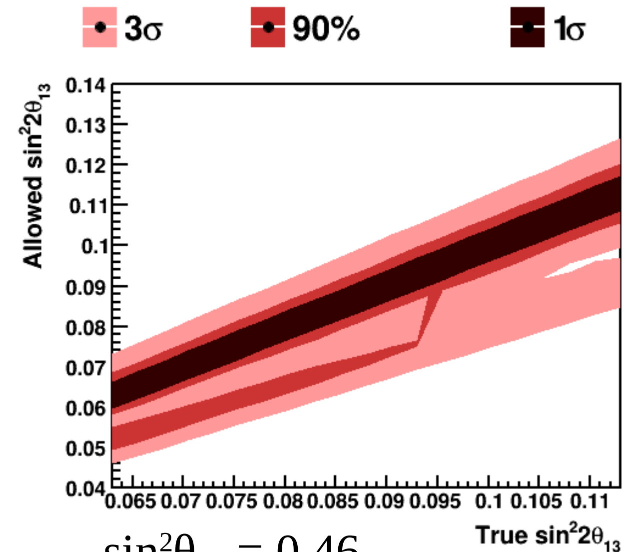


Asimov Studies: θ_{13} Resolution

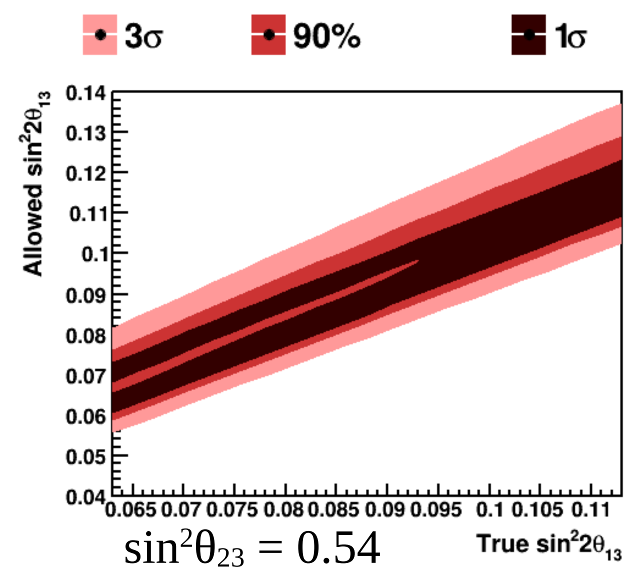
Exposure: 1000 ktMWyrs



$\sin^2\theta_{23} = 0.58$



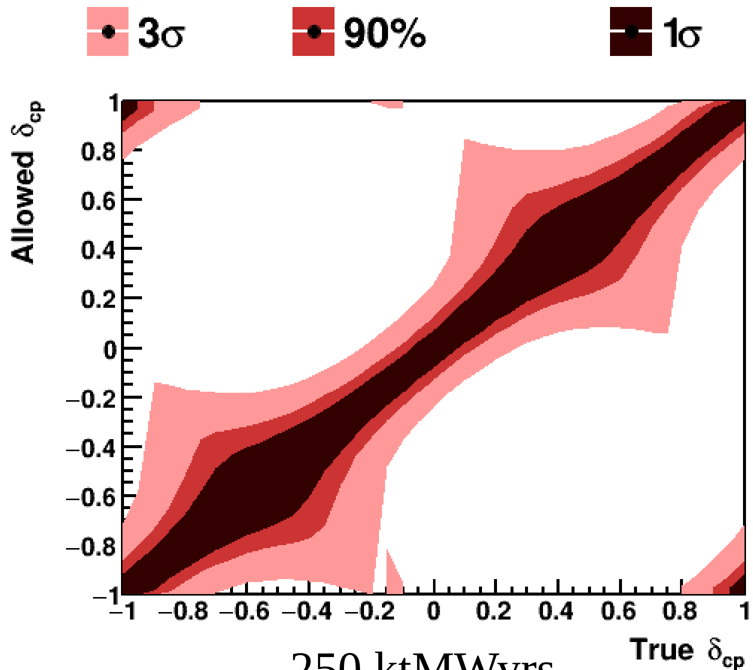
$\sin^2\theta_{23} = 0.46$



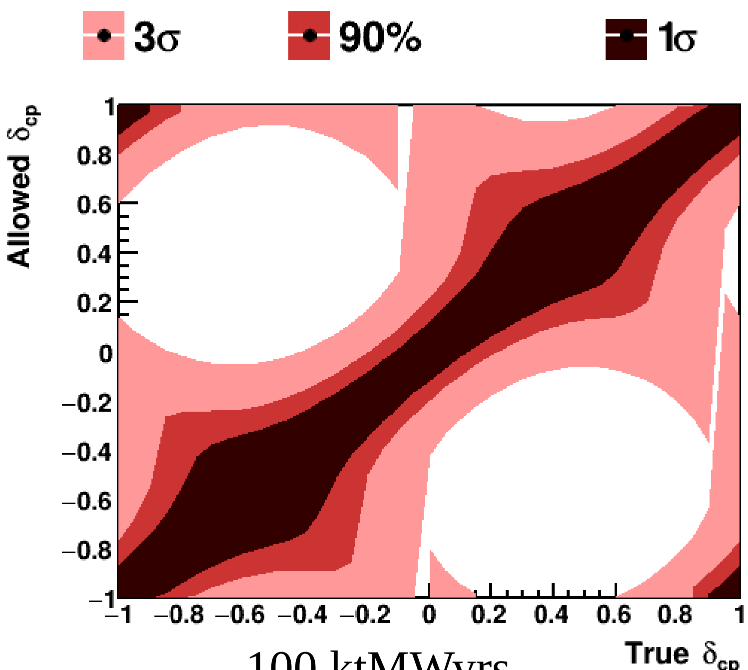
$\sin^2\theta_{23} = 0.54$

Asimov Studies

δ_{CP} Resolution

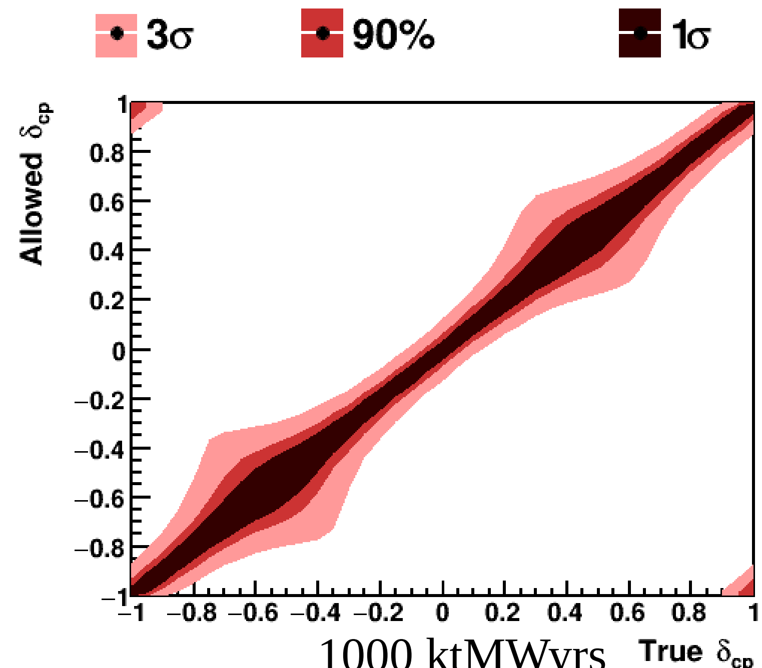


250 ktMWyrs



100 ktMWyrs

$\sin^2\theta_{23} = 0.58$
for all

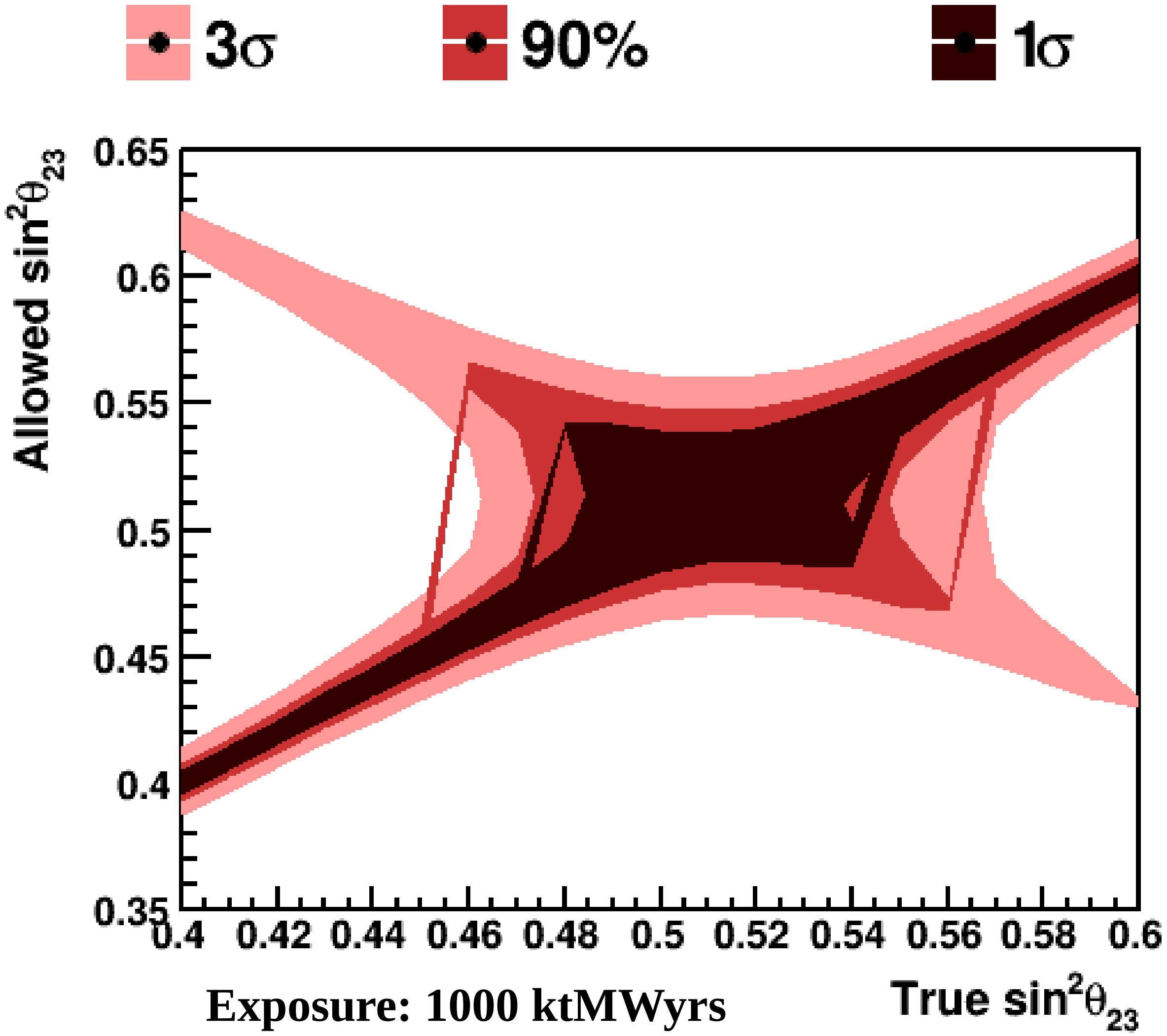


1000 ktMWyrs

UNIVERSITY of ROCHESTER

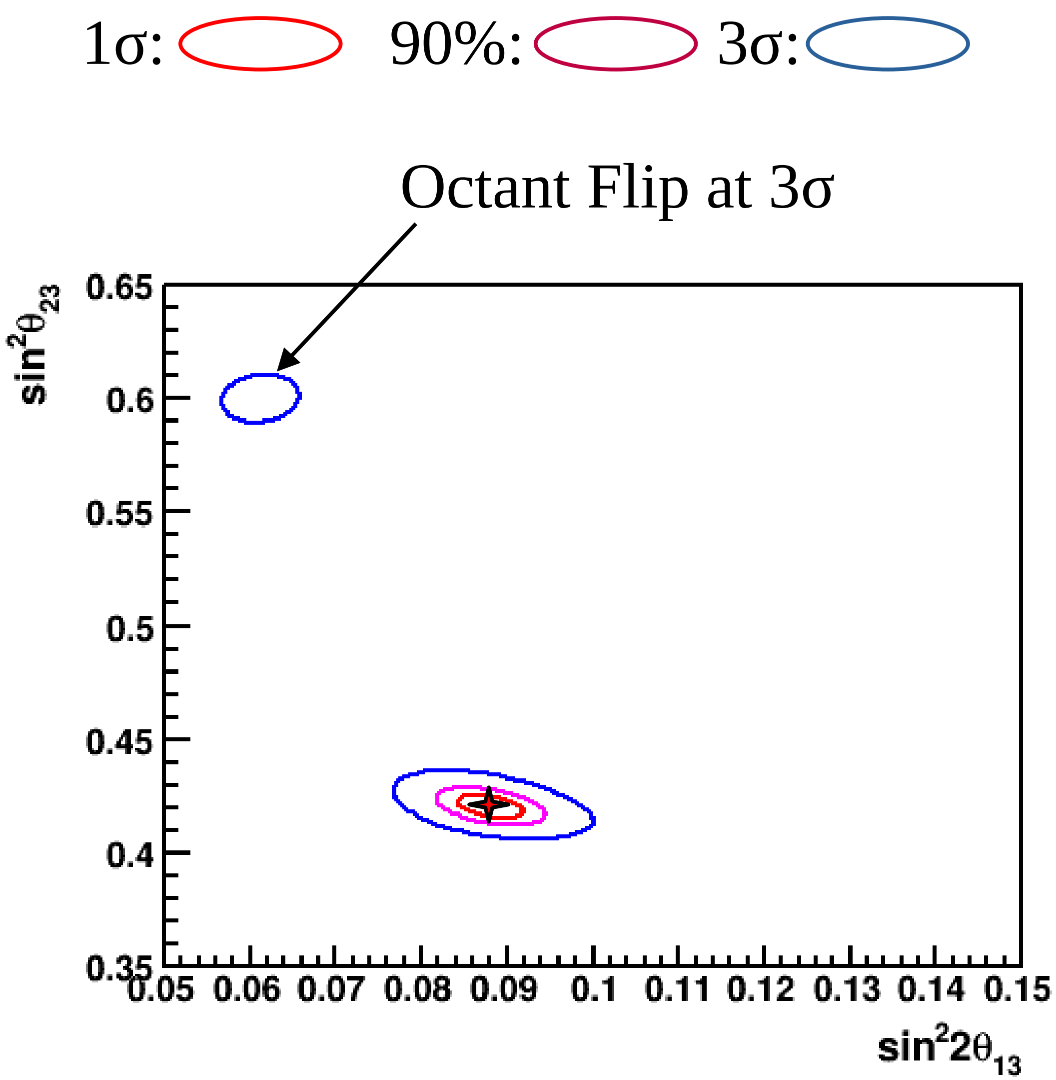
DUNE

Asimov Studies: θ_{23} Resolution



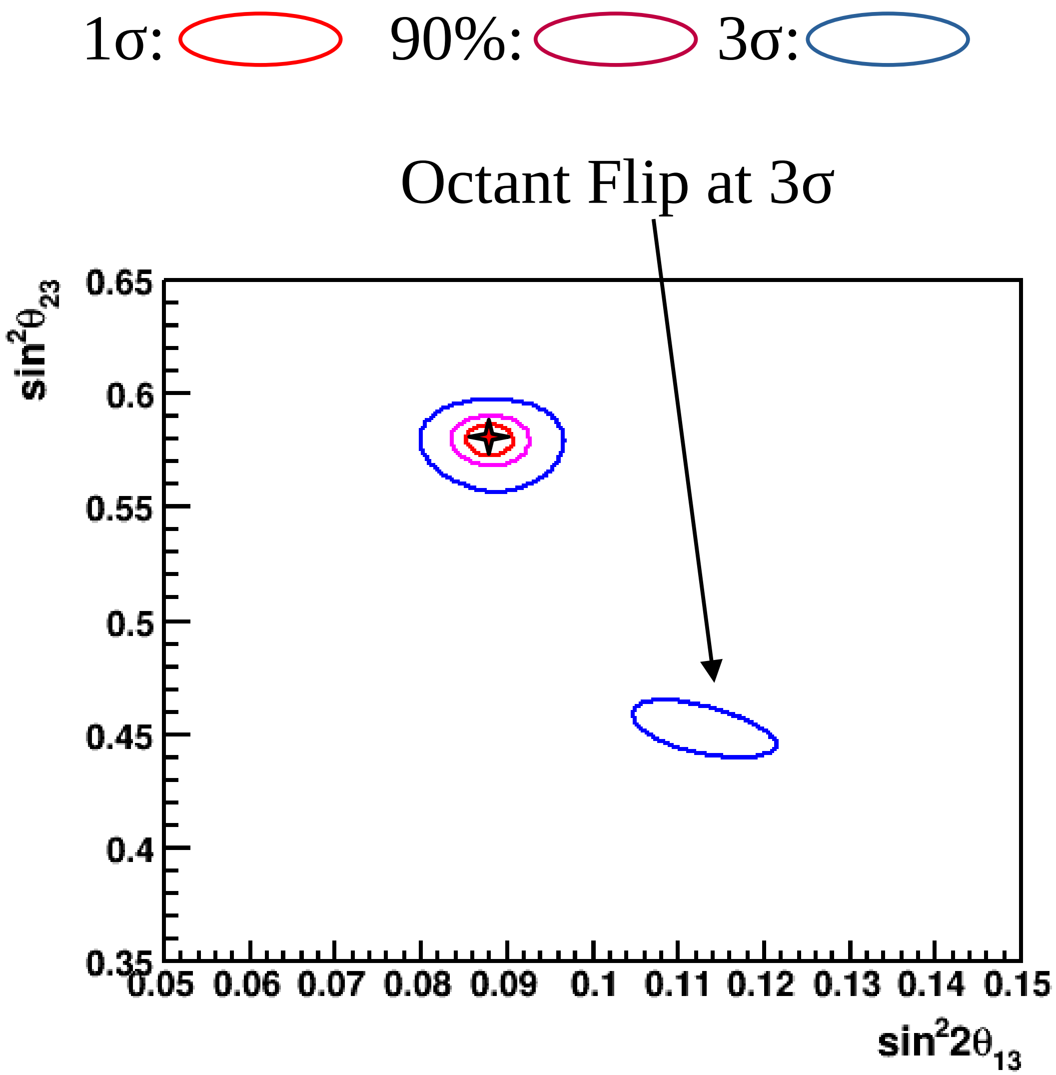
Exposure: 1000 ktMWyrs

Asimov Studies: 2D Scan



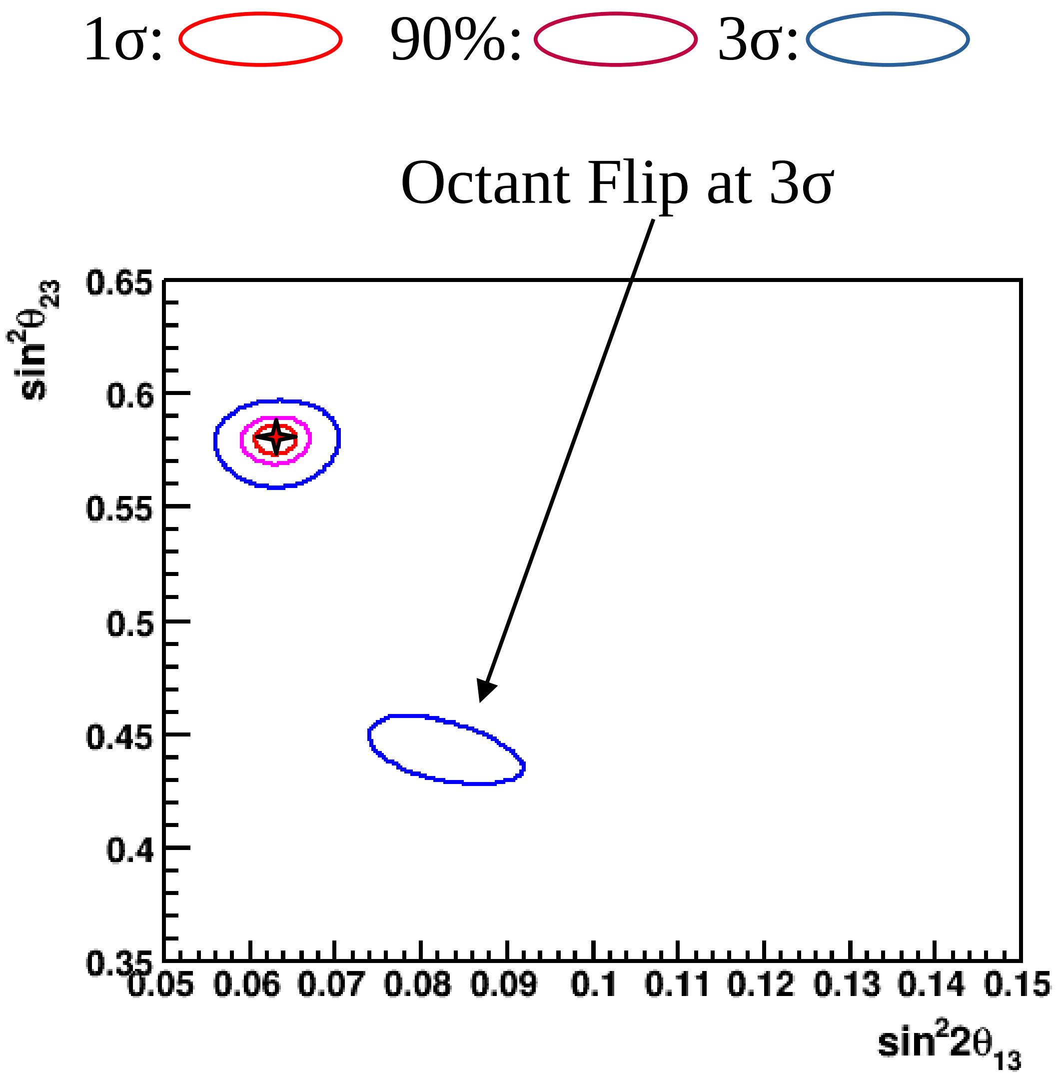
- Scan in θ_{13}-θ_{23} space
- True Point:
  - $\sin^2 2\theta_{13} = 0.088$
  - $\sin^2\theta_{23} = 0.42$
  - All other parameters at nu-fit 4.0
- CLs:
  - 1σ: $\Delta\chi^2 \approx 1$
  - 90%: $\Delta\chi^2 \approx 2.7$
  - 3σ: $\Delta\chi^2 \approx 9$

Asimov Studies: 2D Scan



- Scan in θ_{13}-θ_{23} space
- True Point:
  - $\sin^2 2\theta_{13} = 0.088$
  - $\sin^2\theta_{23} = 0.58$
  - All other parameters at nu-fit 4.0
- CLs:
  - 1σ: $\Delta\chi^2 \approx 1$
  - 90%: $\Delta\chi^2 \approx 2.7$
  - 3σ: $\Delta\chi^2 \approx 9$

Asimov Studies: 2D Scan

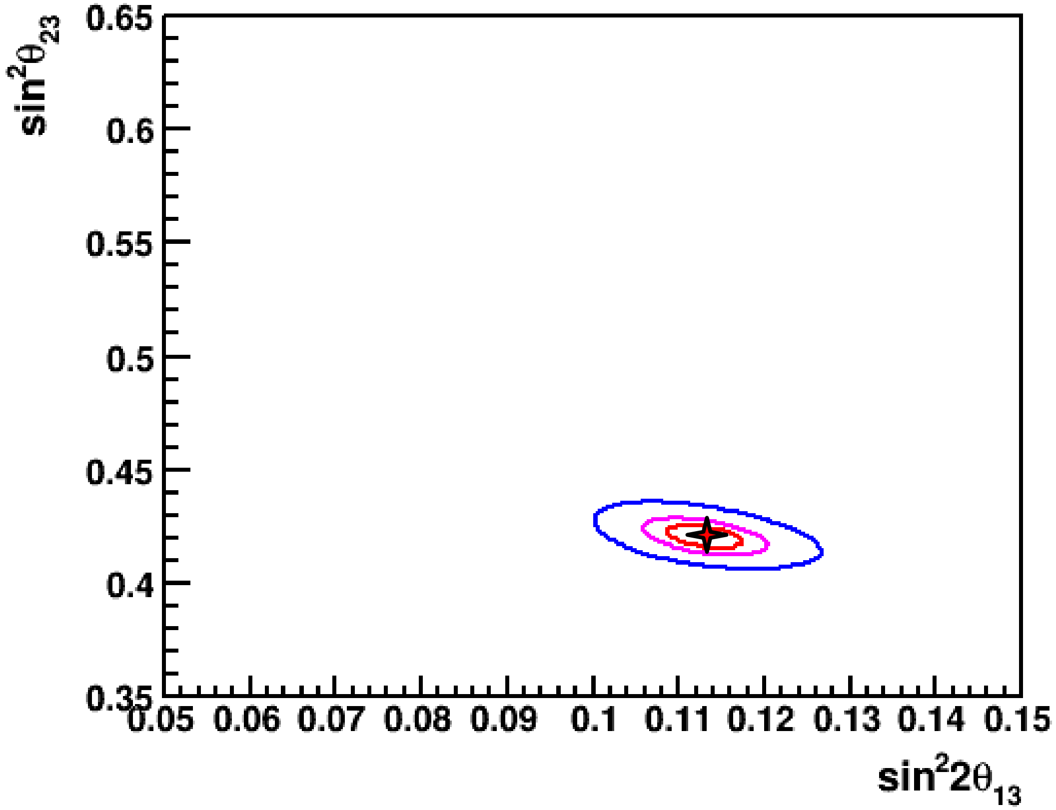


- Scan in θ_{13}-θ_{23} space
- True Point:
  - $\sin^2 2\theta_{13} = 0.063$
  - $\sin^2\theta_{23} = 0.58$
  - All other parameters at nu-fit 4.0
- CLs:
  - 1σ: $\Delta\chi^2 \approx 1$
  - 90%: $\Delta\chi^2 \approx 2.7$
  - 3σ: $\Delta\chi^2 \approx 9$

Asimov Studies: 2D Scan

1σ: 90%: 3σ:

NO Octant Flip at 3σ



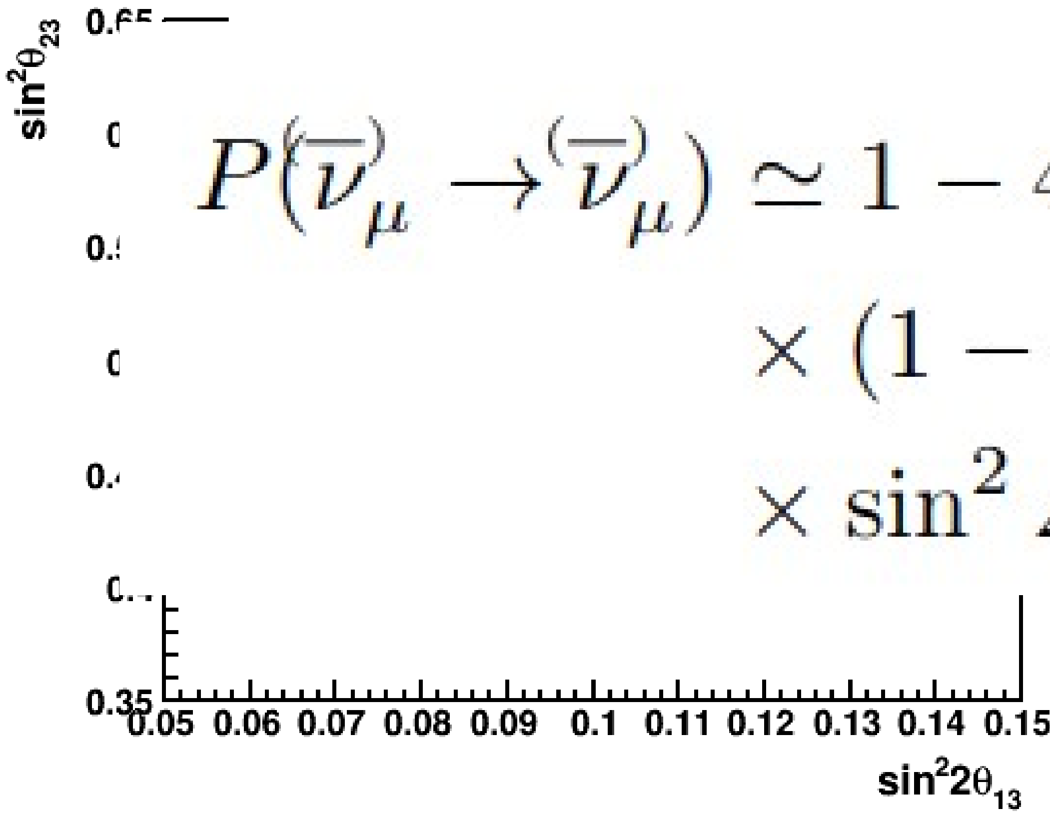
- Scan in θ_{13}-θ_{23} space
- True Point:
  - $\sin^2 2\theta_{13} = 0.113$
  - $\sin^2\theta_{23} = 0.42$
  - All other parameters at nu-fit 4.0
- CLs:
  - 1σ: $\Delta\chi^2 \approx 1$
  - 90%: $\Delta\chi^2 \approx 2.7$
  - 3σ: $\Delta\chi^2 \approx 9$

Asimov Studies: 2D Scan

1σ: ⬭ 90%: ⬭ 3σ: ⬭

- Scan in θ_{13}-θ_{23} space

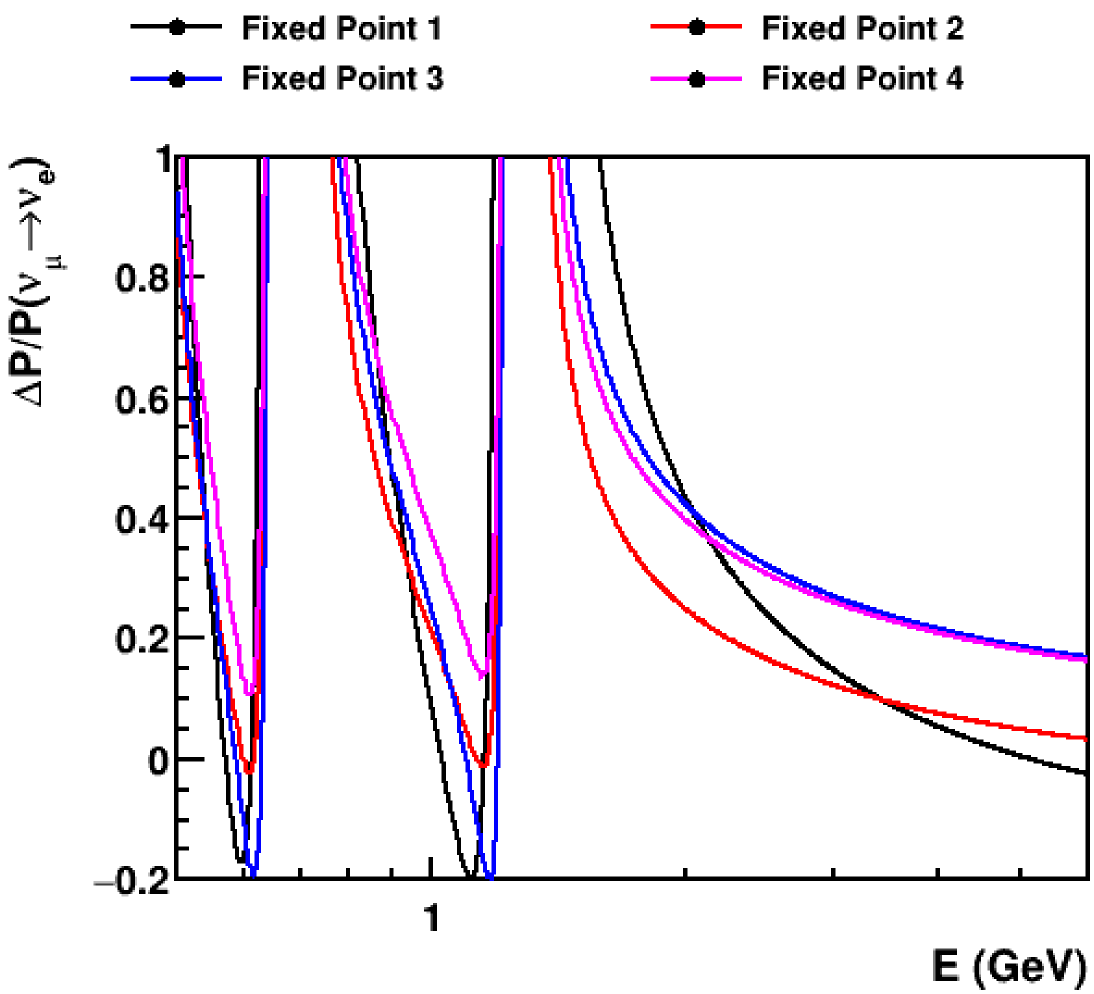
Why no octant flip? ν_μ disappearance



$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times (1 - \cos^2\theta_{13}\sin^2\theta_{23}) \times \sin^2\Delta_{atm}$$

- 1σ: $\Delta\chi^2 \approx 1$
- 90%: $\Delta\chi^2 \approx 2.7$
- 3σ: $\Delta\chi^2 \approx 9$

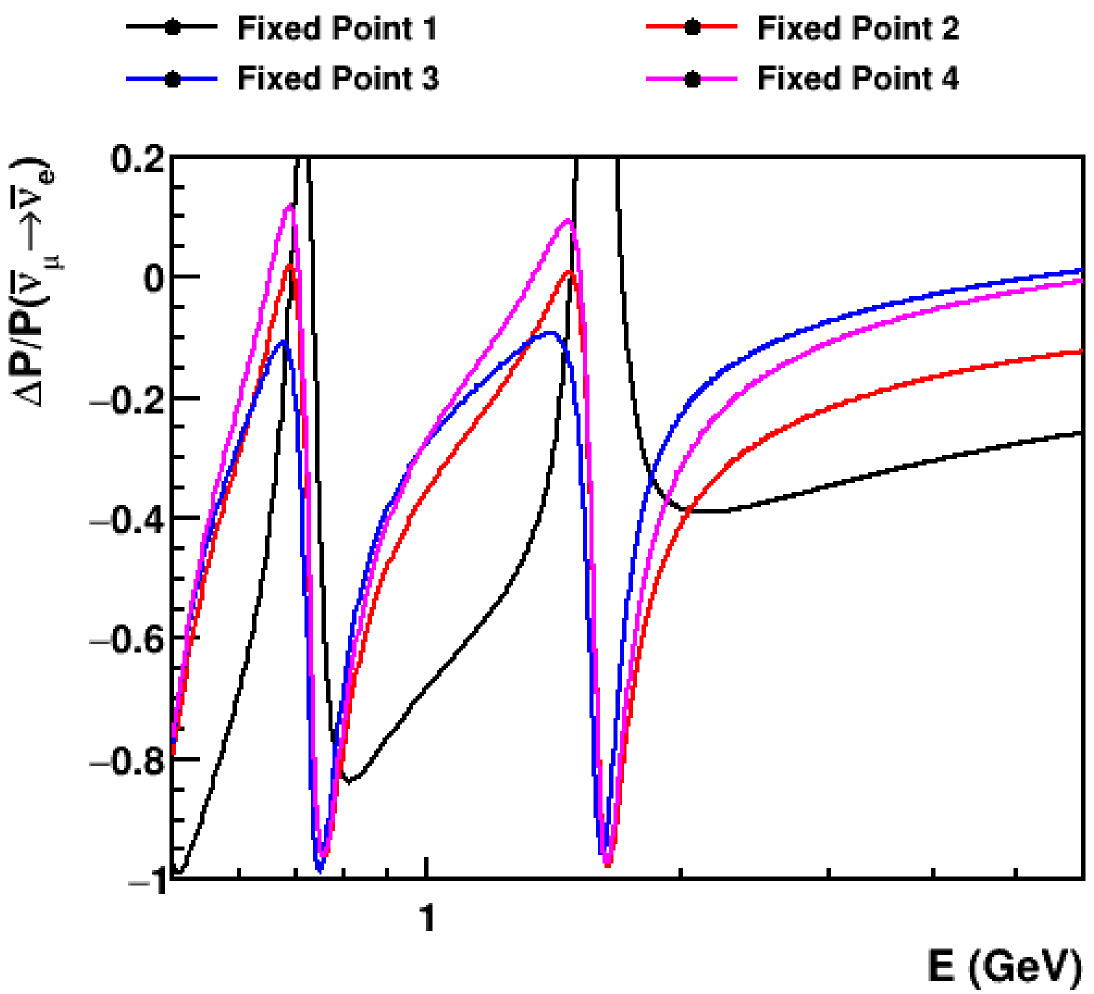
Oscillation Probability Plots



- $\Delta P/P = (P(\text{fixed}) - P(\text{normal}))/P(\text{normal})$
- Normal point:
  - NO, ssth23 = 0.50, $\delta_{CP} = 0$, all others at nufit
- Fixed Points: All NO

	ss2th13	ssth23	δ_{CP}
1	0.088	0.50	-π/2
2	0.088	0.50	-π/4
3	0.088	0.58	-π/4
4	0.113	0.44	-π/4

Oscillation Probability Plots



- $\Delta P/P$ = (P(fixed) – P(normal))/P(normal)
- Normal point:
  - NO, ssth23 = 0.50, δ_{CP} = 0, all others at nufit
- Fixed Points: All NO

	ss2th13	ssth23	δ_{CP}
1	0.088	0.50	$-\pi/2$
2	0.088	0.50	$-\pi/4$
3	0.088	0.58	$-\pi/4$
4	0.113	0.44	$-\pi/4$

New Physics? Indirect Test of PMNS Non-unitarity

Jeremy Fleishhacker

New Physics? Indirect Test of PMNS Non-unitarity

- PMNS matrix: $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

New Physics? Indirect Test of PMNS Non-unitarity

- PMNS matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Assuming unitarity allows parameterization with familiar mixing angles/CP phase

New Physics? Indirect Test of PMNS Non-unitarity

- PMNS matrix: $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
- Assuming unitarity allows parameterization with familiar mixing angles/CP phase
- If unitarity, DUNE measures

New Physics? Indirect Test of PMNS Non-unitarity

- PMNS matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Assuming unitarity allows parameterization with familiar mixing angles/CP phase
- If unitarity, DUNE measures
  - via ν_μ disappearance: $4\left|U_{\mu 3}\right|^2\left(1-\left|U_{\mu 3}\right|^2\right)$

$$= 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1-\cos^2\theta_{13}\sin^2\theta_{23}\right)$$

New Physics? Indirect Test of PMNS Non-unitarity

- PMNS matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Assuming unitarity allows parameterization with familiar mixing angles/CP phase
- If unitarity, DUNE measures
  - via ν_μ disappearance: $4\,|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2\right)$

$$= 4 \cos^2\theta_{13} \sin^2\theta_{23} \left(1 - \cos^2\theta_{13} \sin^2\theta_{23}\right)$$

  - via ν_e appearance: $4\,|U_{e3}|^2\,|U_{\mu 3}|^2 = \sin^2 2\theta_{13} \sin^2\theta_{23}$

New Physics? Indirect Test of PMNS Non-unitarity

- If unitarity, DUNE measures
  - via ν_μ disappearance: $4\left|U_{\mu 3}\right|^2\left(1-\left|U_{\mu 3}\right|^2\right)$
    $= 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1-\cos^2\theta_{13}\sin^2\theta_{23}\right)$
  - via ν_e appearance: $4\left|U_{e3}\right|^2\left|U_{\mu 3}\right|^2 = \sin^2 2\theta_{13}\sin^2\theta_{23}$
- Daya Bay (reactor SBL) measures:
  - via $\bar{\nu}_e$ disappearance: $4\left|U_{e3}\right|^2\left(1-\left|U_{e3}\right|^2\right) = \sin^2 2\theta_{13}$

New Physics? Indirect Test of PMNS Non-unitarity

- If unitarity, DUNE measures
  - via ν_μ disappearance: $4\,|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2\right)$
    $= 4\cos^2\theta_{13}\sin^2\theta_{23}\,(1 - \cos^2\theta_{13}\sin^2\theta_{23})$
  - via ν_e appearance: $4\,|U_{e3}|^2\,|U_{\mu 3}|^2 = \sin^2 2\theta_{13}\sin^2\theta_{23}$
- Daya Bay (reactor SBL) measures:
  - via $\bar{\nu}_e$ disappearance: $4\,|U_{e3}|^2 \left(1 - |U_{e3}|^2\right) = \sin^2 2\theta_{13}$
- DUNE and Daya Bay obtain independent measurements of θ_{13}

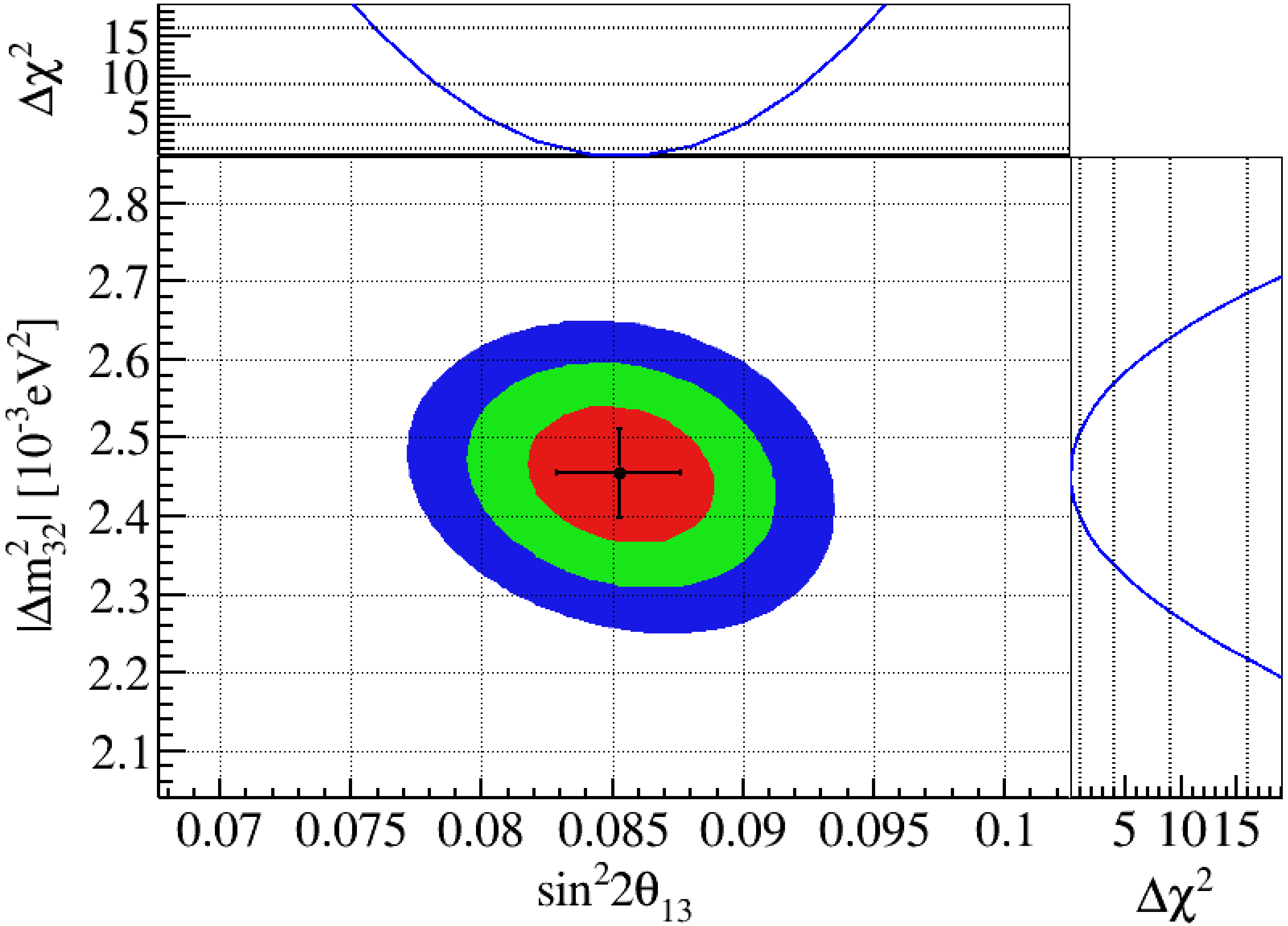
New Physics? Indirect Test of PMNS Non-unitarity

- If unitarity, DUNE measures
  - via ν_μ disappearance: $4\left|U_{\mu 3}\right|^2\left(1-\left|U_{\mu 3}\right|^2\right)$
  $= 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1-\cos^2\theta_{13}\sin^2\theta_{23}\right)$
  - via ν_e appearance: $4\left|U_{e3}\right|^2\left|U_{\mu 3}\right|^2 = \sin^2 2\theta_{13}\sin^2\theta_{23}$
- Daya Bay (reactor SBL) measures:
  - via $\bar{\nu}_e$ disappearance: $4\left|U_{e3}\right|^2\left(1-\left|U_{e3}\right|^2\right) = \sin^2 2\theta_{13}$
- DUNE and Daya Bay obtain independent measurements of θ_{13}
- If unitarity, θ_{13} measurements should agree

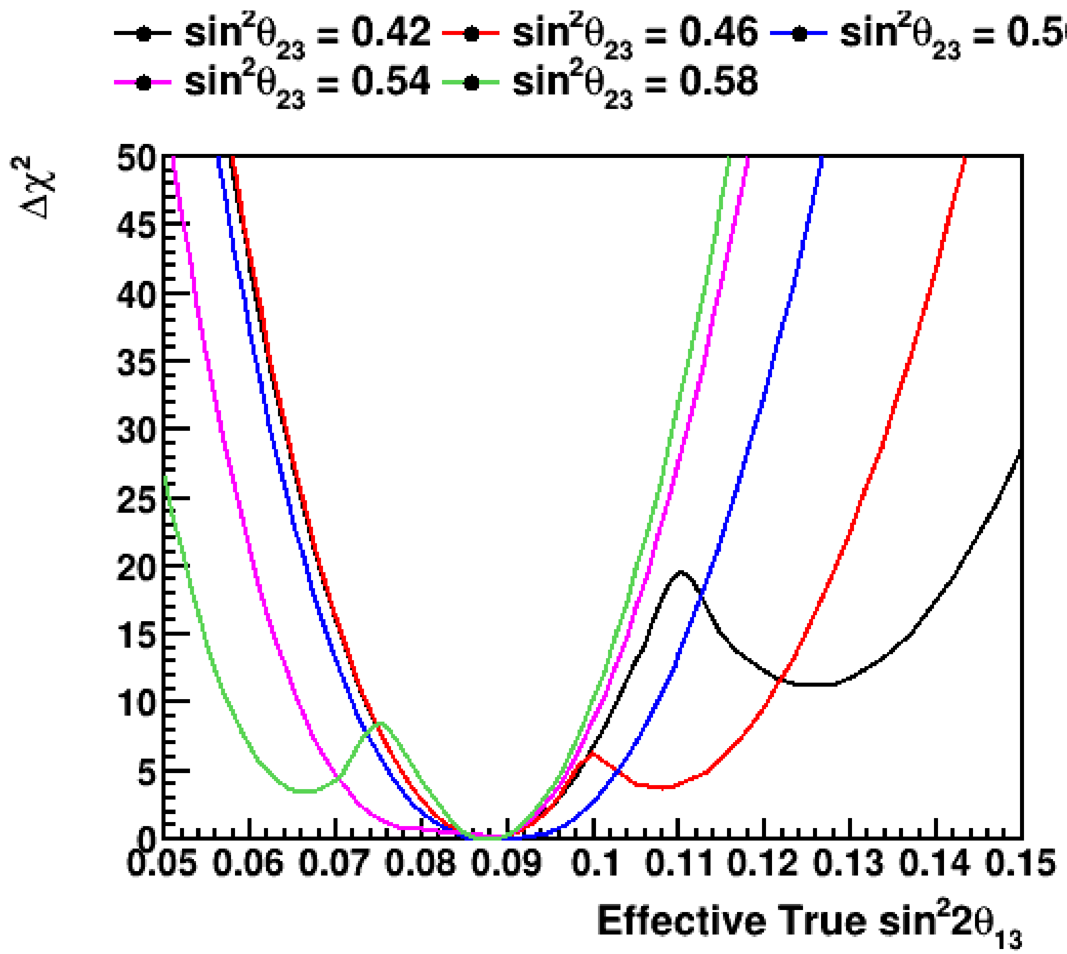
New Physics? Indirect Test of PMNS Non-unitarity

- If unitarity, DUNE measures
  - via ν_μ disappearance: $4\,|U_{\mu 3}|^2\left(1-|U_{\mu 3}|^2\right)$
    $= 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1-\cos^2\theta_{13}\sin^2\theta_{23}\right)$
  - via ν_e appearance: $4\,|U_{e3}|^2\,|U_{\mu 3}|^2 = \sin^2 2\theta_{13}\sin^2\theta_{23}$
- Daya Bay (reactor SBL) measures:
  - via $\bar{\nu}_e$ disappearance: $4\,|U_{e3}|^2\left(1-|U_{e3}|^2\right) = \sin^2 2\theta_{13}$
- DUNE and Daya Bay obtain independent measurements of θ_{13}
- **If θ_{13} measurements are in tension, non-unitarity**

Daya Bay's θ_{13} Measurement

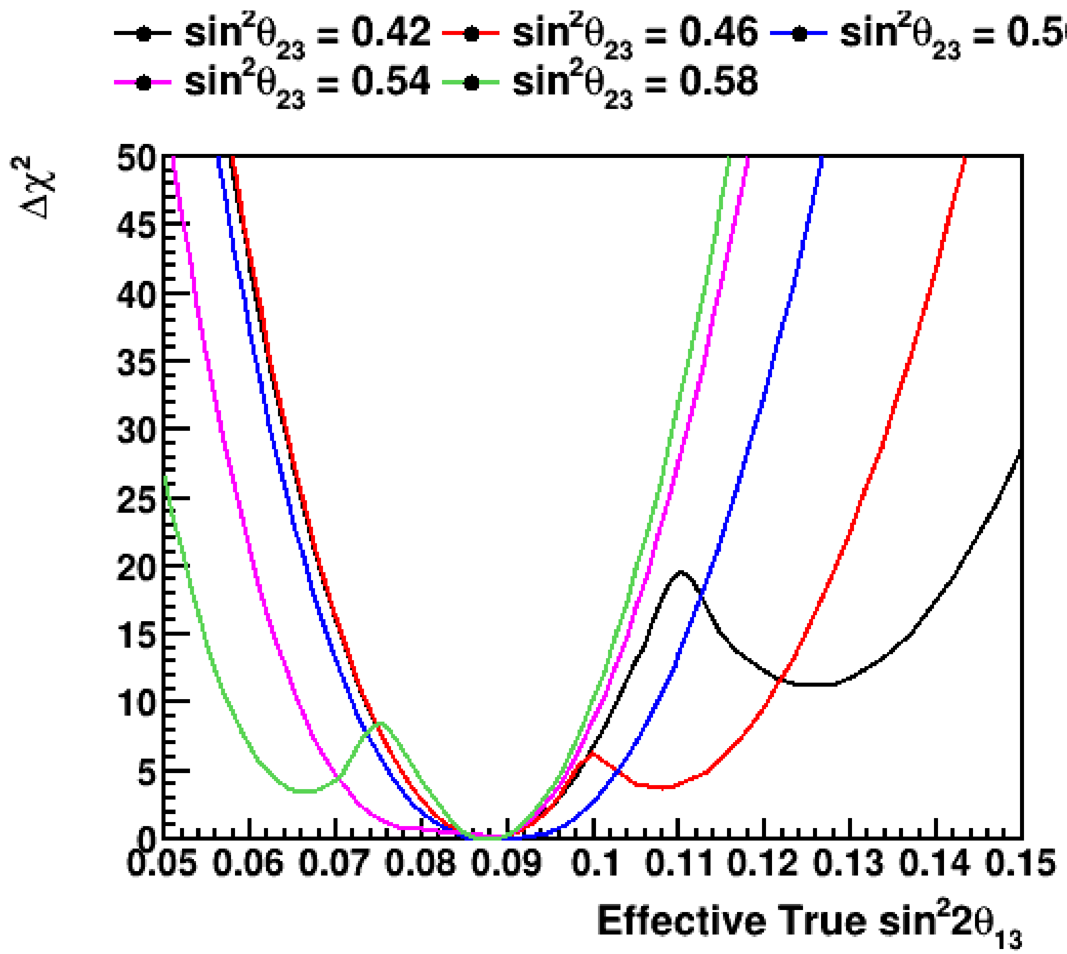


DUNE's Sensitivity to PMNS Non-unitarity



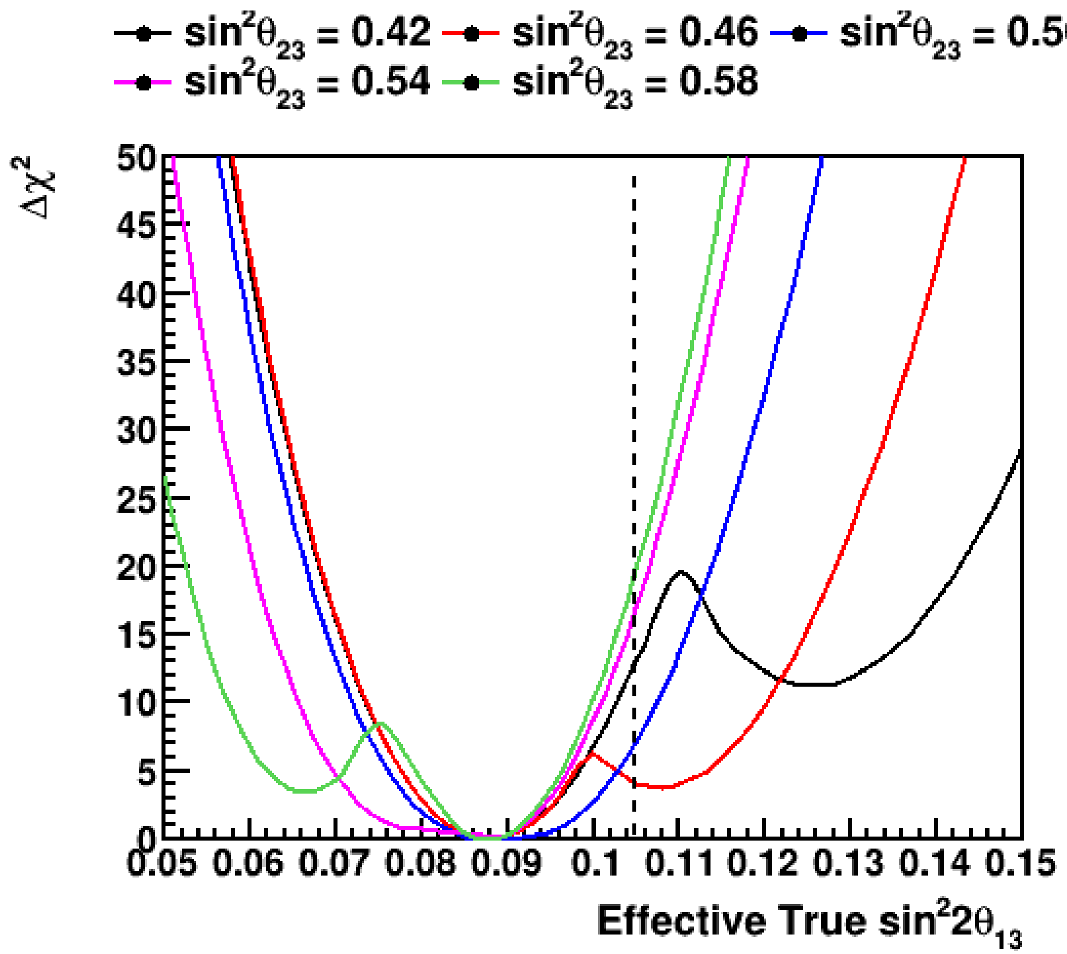
- Asimov fits at 21 eff. true θ_{13} and 5 eff. true θ_{23} points.
  - $\Delta\chi^2$ is difference between θ_{13} penalty χ^2 and no penalty χ^2
- 1DOF $\Delta\chi^2$?
- Octant flip decreases sensitivity for
  - High θ_{13}, low θ_{23}
  - Low θ_{13}, high θ_{23}

DUNE's Sensitivity to PMNS Non-unitarity



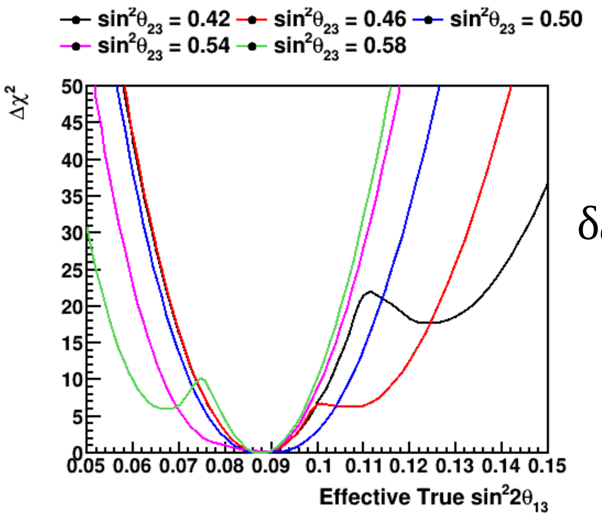
- Octant flip asymmetry: higher sensitivity for high/low θ_{13}/θ_{23} than low/high θ_{13}/θ_{23}
- Higher sensitivity for non-maximal, non-octant-flipping θ_{23}

DUNE's Sensitivity to PMNS Non-unitarity

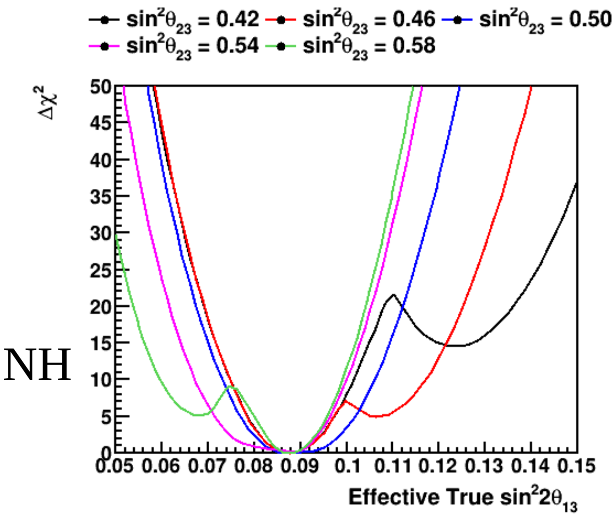


- If T2K's center ($\sin^2 2\theta_{13} = 0.105$) is accurate to accelerator LBL effective θ_{13}:
  - $2\sigma - 4.5\sigma$ tension
  - Best case: highly non-maximal upper octant θ_{23}
  - Worst case: somewhat non-maximal lower octant θ_{23}

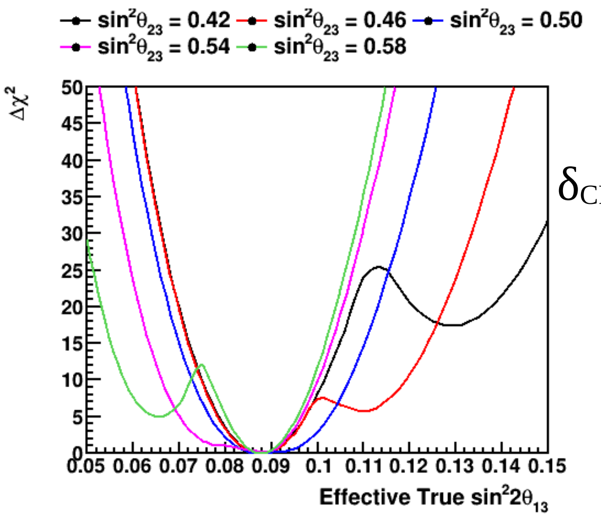
Sensitivity Largely Independent of δ_{CP}/Mass Hierarchy



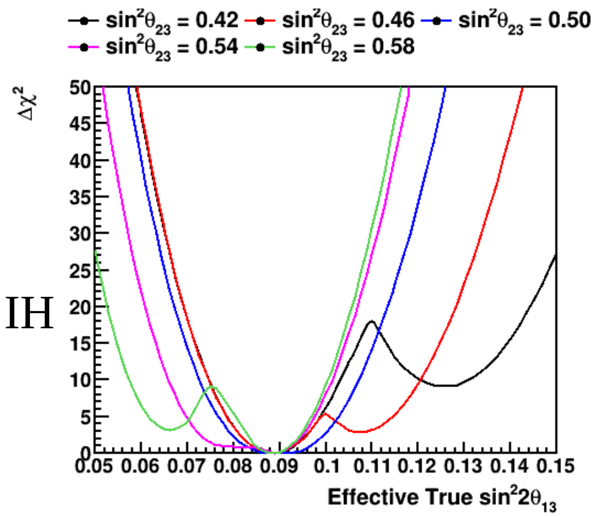
$\delta_{CP} = 0$, NH



$\delta_{CP} = -\pi/2$, NH



$\delta_{CP} = \pi/2$, NH



$\delta_{CP} = 0$, IH

Next Steps

- More thoroughly interpret $\Delta\chi^2$ of tension with Daya Bay
- Report accurate DUNE measurement resolutions for θ_{13}, θ_{23}, δ_{cp}
- Add two fixed points to prob plots to show MO and δ_{CP} effect
- Compare single point throws and Asimov scan for δ_{CP} resolution
  - Degeneracy present in throws, not in Asimov scan
- Reproduce T2K JCP plots for DUNE

Conclusions

- DUNE's precision requires understanding correlations and degeneracies in 4D oscillation parameter space
  - Degenerate δ_{cp} and correlated $\theta_{13} - \theta_{23}$
  - Investigated via single true point throws and scanning Asimov studies
- Exhibited DUNE's θ_{13} and θ_{23} resolution (with degeneracies) at 1000 ktMWyrs, δ_{CP} measurement resolution at 100, 250, and 1000 ktMWyrs
- Fixed point $\Delta P/P$ plots show wide energy spectrum critical to resolving $\theta_{13} - \theta_{23}$ degeneracy
- DUNE highly sensitive to an indirect test of PMNS non-unitarity when combined with Daya Bay's θ_{13} result
  - Highly dependent on true parameter values

Backups

Neutrino Mixing

- Can parameterize PMNS matrix assuming unitarity (**big assumption**):

$$U_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\mathrm{I}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\mathrm{II}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathrm{III}}$$

- Unitarity means only three flavor/mass states
- Non-unitarity → new physics!

Jeremy Fleishhacker

Neutrino Oscillation

- DUNE can't measure these mixing parameters directly
- χ^2 fit used to obtain mixing parameters from appearance/disappearance measurements

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

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

$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$

Neutrino Oscillation

- DUNE can't measure these mixing parameters directly
- χ^2 fit used to obtain mixing parameters from appearance/disappearance measurements
- Parameter dependencies can lead to errors in fits (oops!)

$$P(\nu_\mu \rightarrow \nu_e) \simeq \boxed{\sin^2\theta_{23}\sin^2 2\theta_{13}} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2$$
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31} + \delta_{CP})$$
$$+ \cos^2\theta_{23}\sin^2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

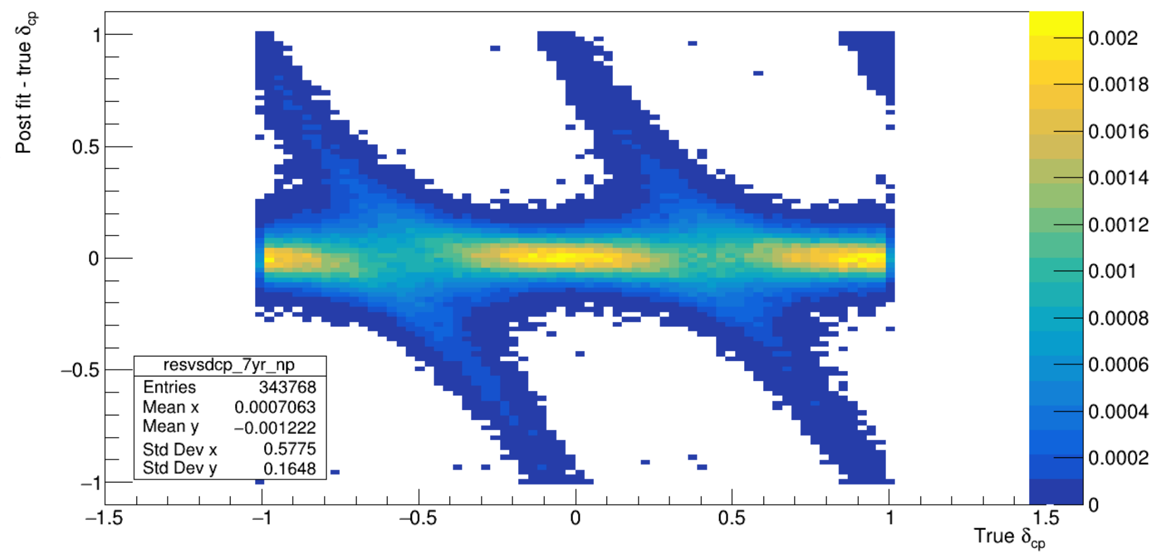
$$a = G_F N_e/\sqrt{2}$$
$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$

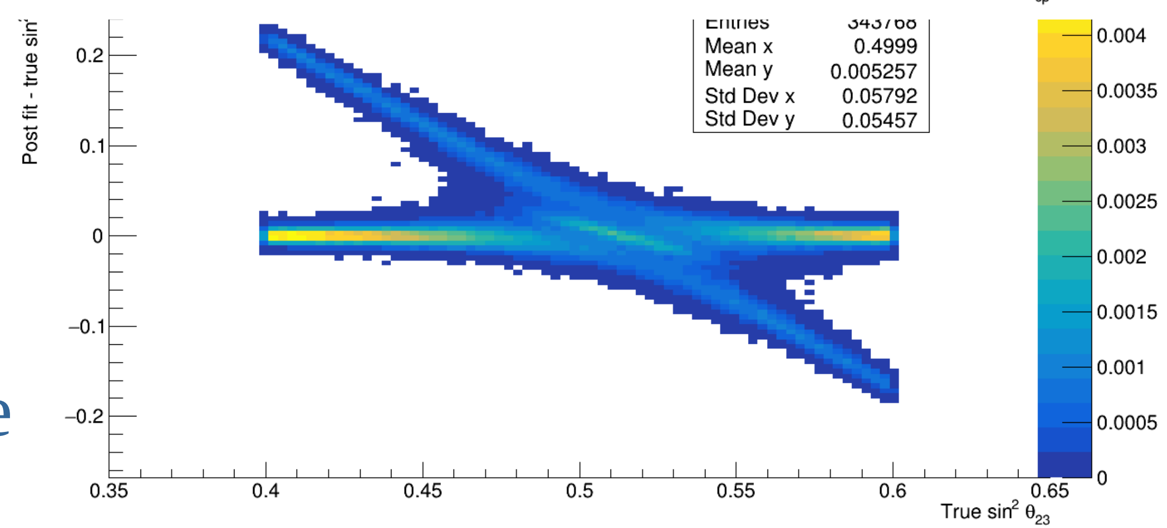
Parameter Correlations and Degeneracies: Why Do We Care?

- DUNE will have the ability to make precision measurements of these parameters, including the level of charge-parity (CP) violation for leptons.
- Previous measurements of oscillation parameters have been treated independently, omitting possible correlations that become significant as experimental precision increases.
- Understanding how DUNE fits of oscillation parameters are affected by these correlations enables more accurate evaluation of DUNE measurement resolutions and sensitivity to new physics.

Correlations/Degeneracies: TDR Analysis

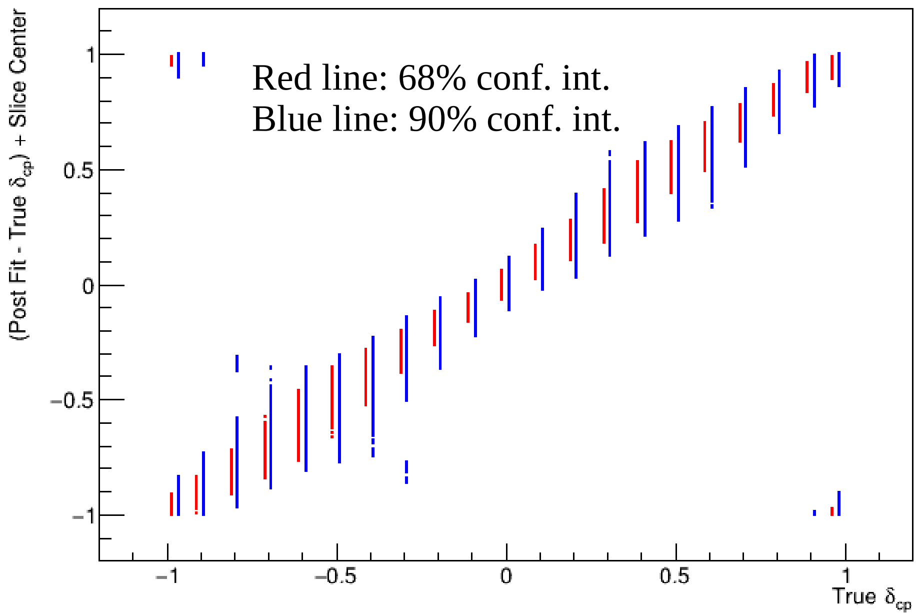
- Resolution plots using long baseline (LBL) technical design report (TDR) analysis data
- Simulated experiments (pseudo-experiments) for different sets of true parameter values, post fit (pf) parameter values generated for each set
- TOP: δ_{cp} pf – true vs true
- BOTTOM: $\sin^2\theta_{23}$ pf – true vs true

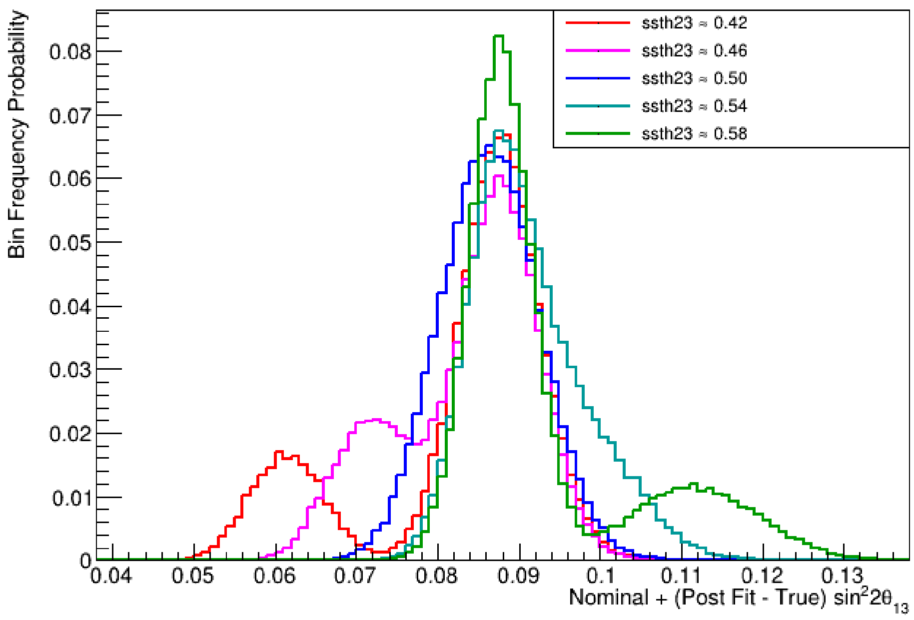




Jeremy Fleishhacker
UNIVERSITY of ROCHESTER

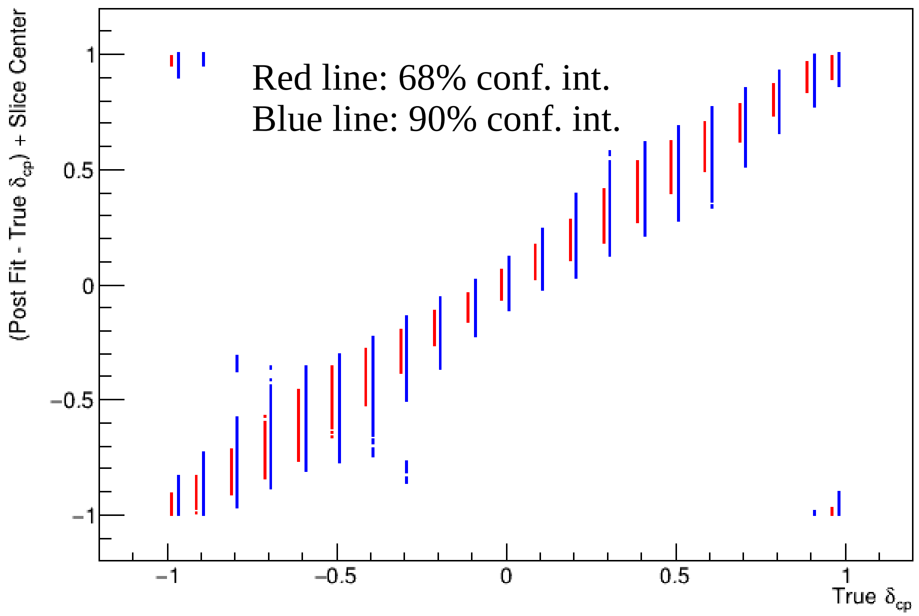
Correlations/Degeneracies: TDR Analysis

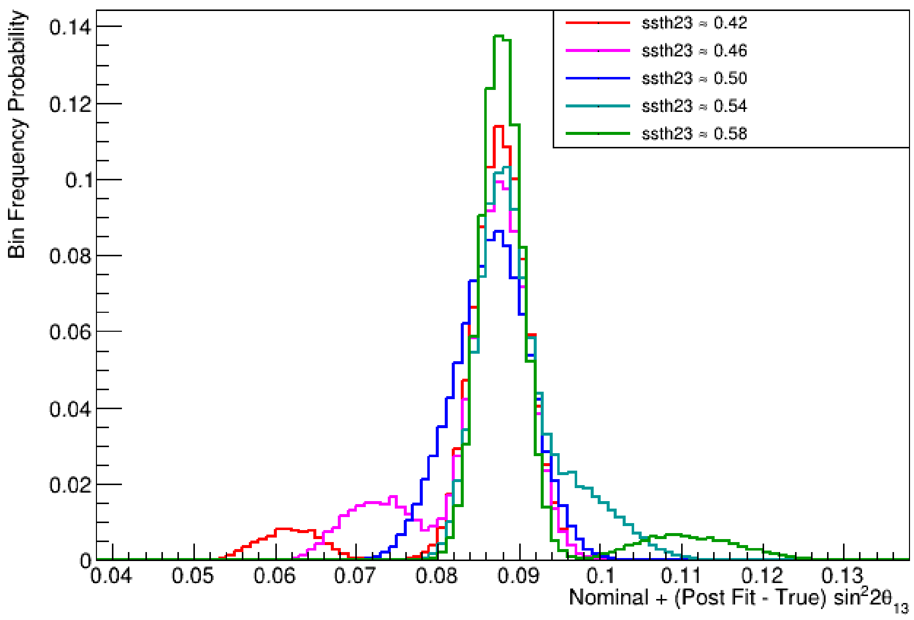




- δ_{cp} degeneracy captured at 90% near true values of -0.8π, -0.7π, -0.4π, -0.3π
- θ_{13} "error mode" significance/position depends on θ_{23}

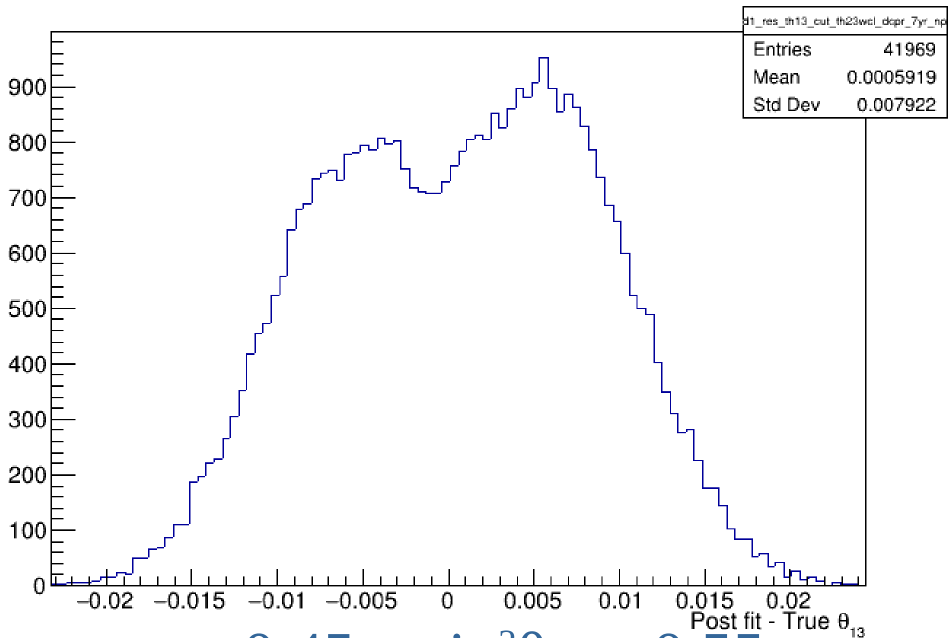
Correlations/Degeneracies: TDR Analysis



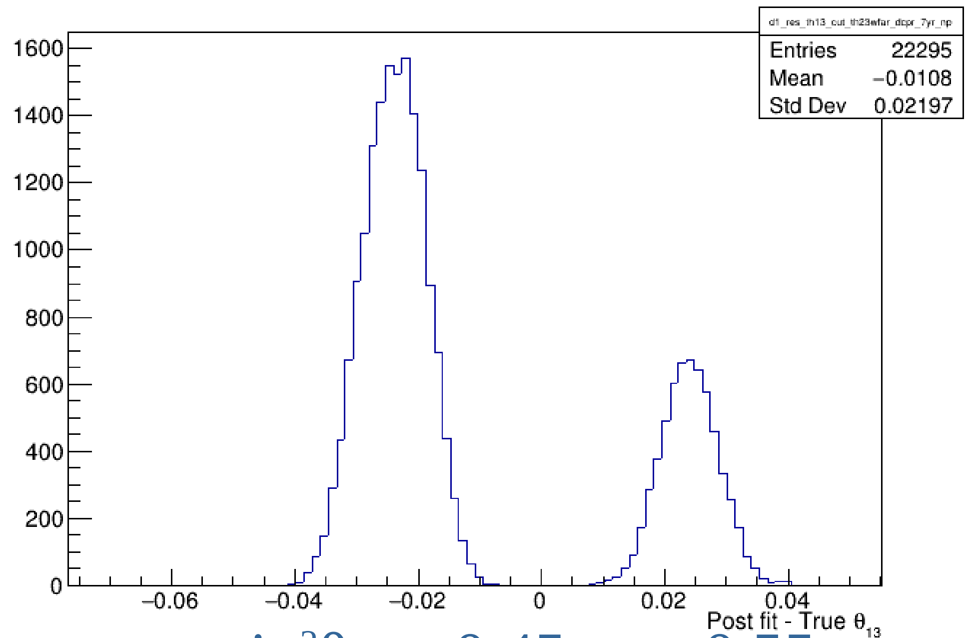


- δ_{cp} degeneracy captured at 90% near true values of -0.8π, -0.7π, -0.4π, -0.3π
- θ_{13} "error mode" significance/position depends on θ_{23} **and exposure**

θ_{23} octant flip effect on θ_{13}



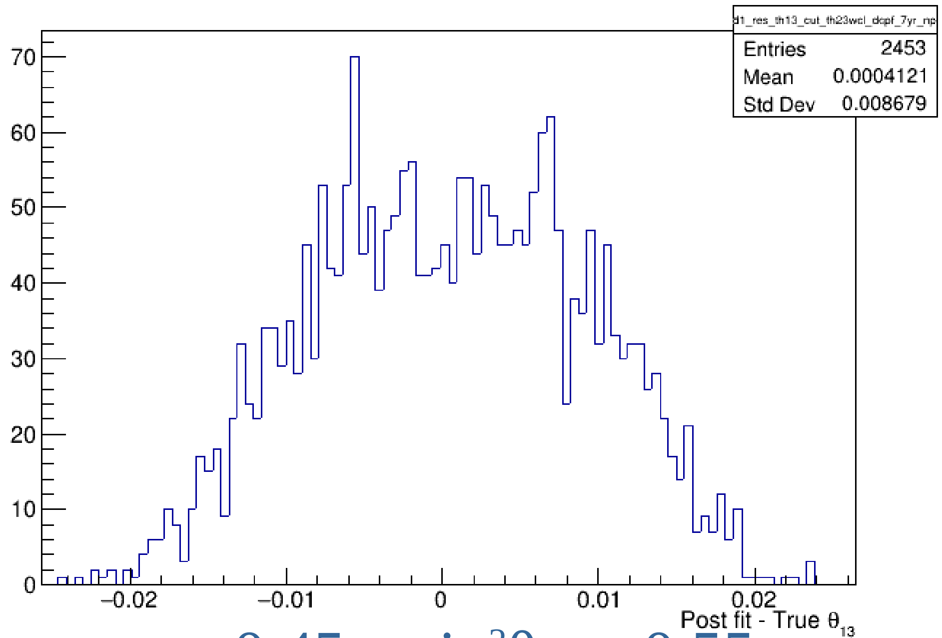
$0.45 < \sin^2\theta_{23} < 0.55$



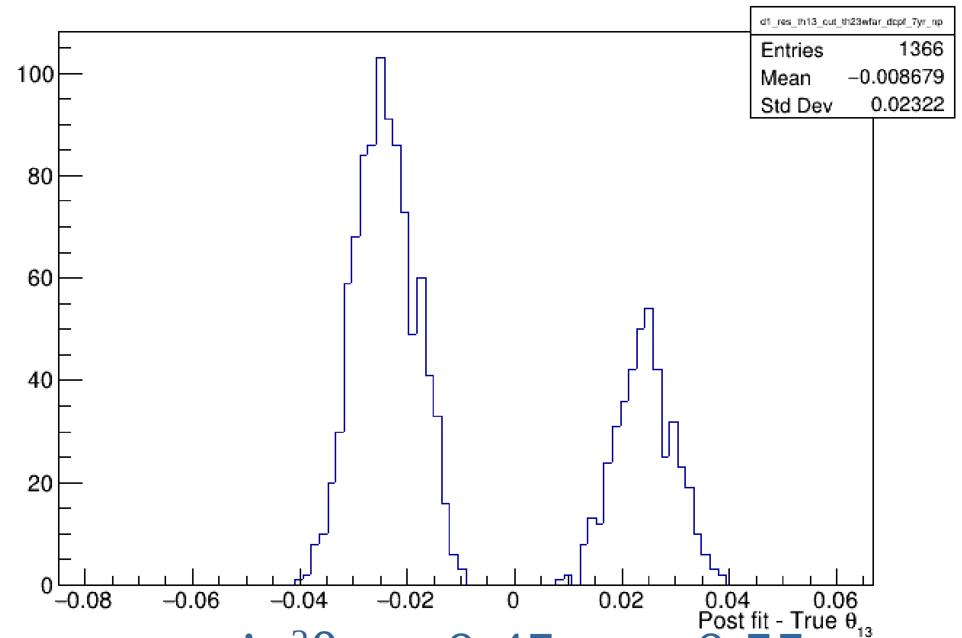
$\sin^2\theta_{23} < 0.45$ or > 0.55

- Above: θ_{13} Post fit - true distributions, θ_{23} measured in wrong octant
- θ_{23} octant error leads to bimodality in θ_{13} measurement
- Less maximal θ_{23} = greater bimodality
- Asymmetry between modes on right plot: what favors under- vs over-estimation?

δ_{cp} effect?



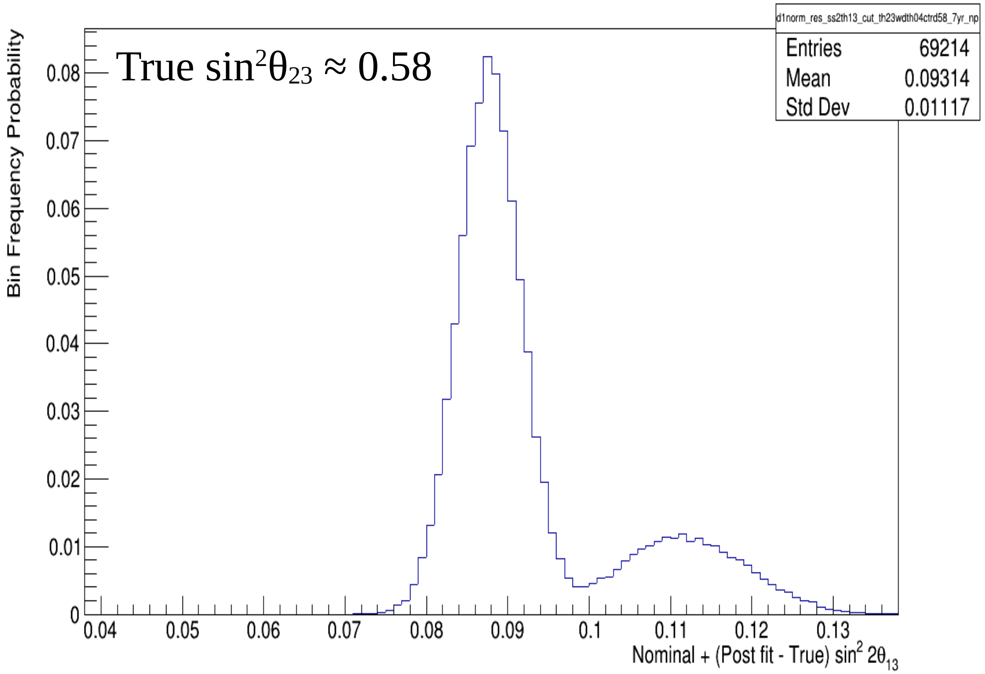
$0.45 < \sin^2\theta_{23} < 0.55$



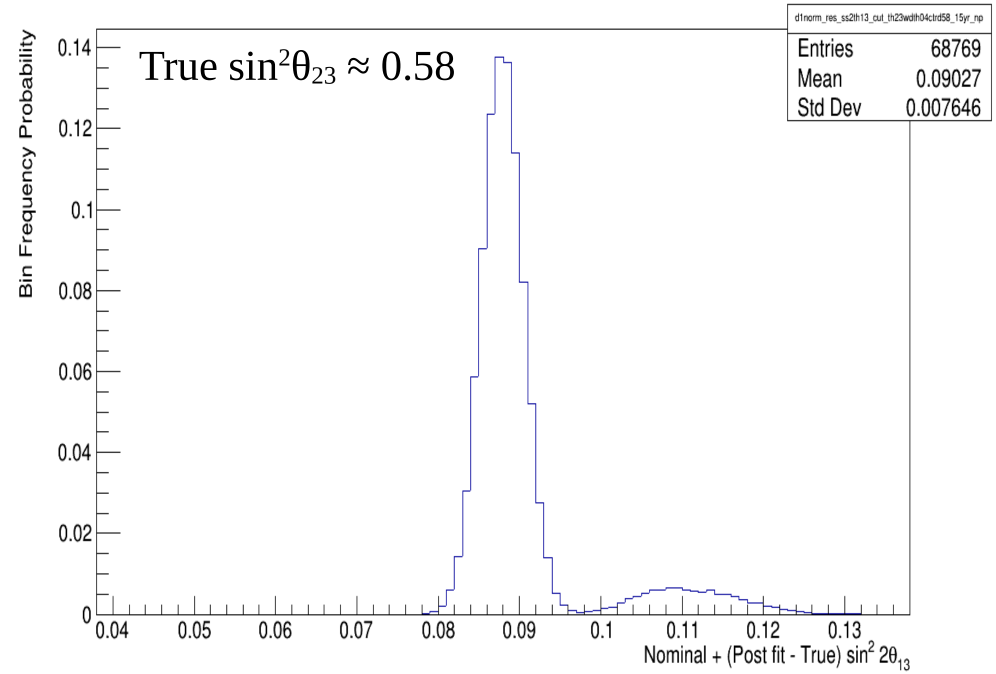
$\sin^2\theta_{23} < 0.45$ or > 0.55

- Flipping δ_{cp} appears to be uncorrelated with θ_{13} measurement
- δ_{cp} degeneracy appears to be independent of θ_{13}-θ_{23} correlation

θ_{23} octant flip effect on θ_{13}



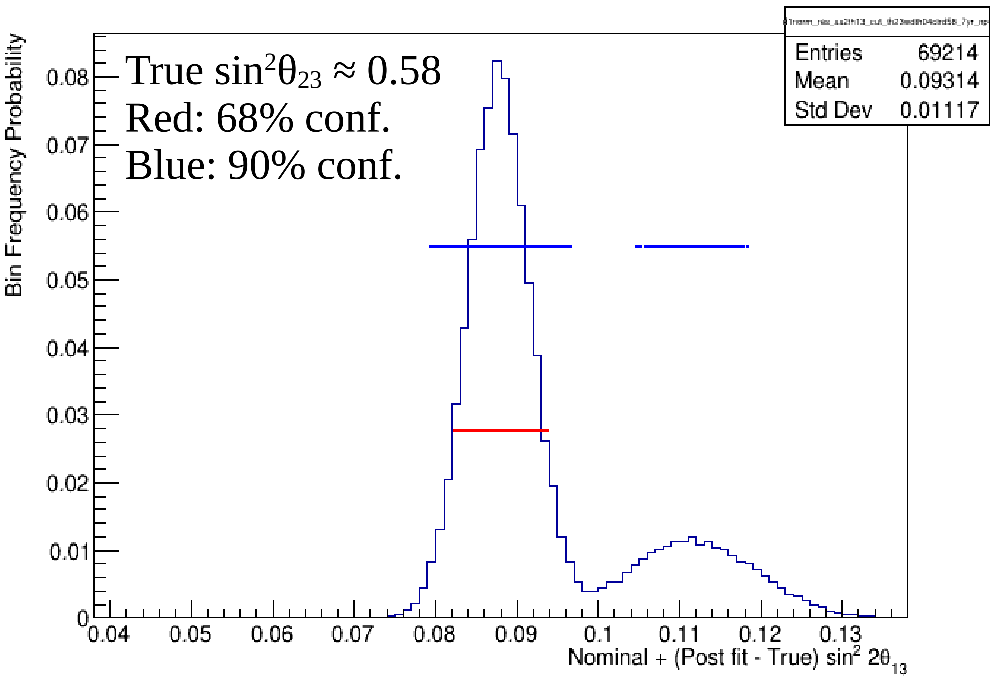
7 year exposure



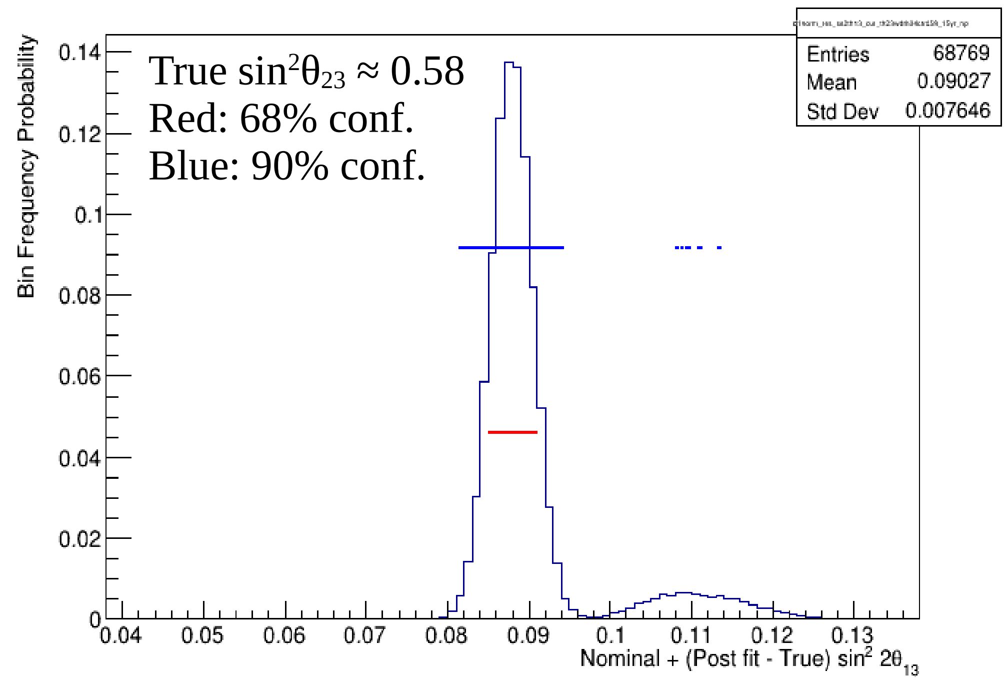
15 year exposure

- $\sin^2 2\theta_{13}$ post fit distribution shown at fixed $\sin^2\theta_{23} \approx 0.58$.
- Underestimated $\sin^2\theta_{23}$ corresponds to overestimated $\sin^2 2\theta_{13}$, gap between modes due to disfavored maximal θ_{23}
- Increasing exposure decreases octant error significance

θ_{23} octant flip effect on θ_{13}



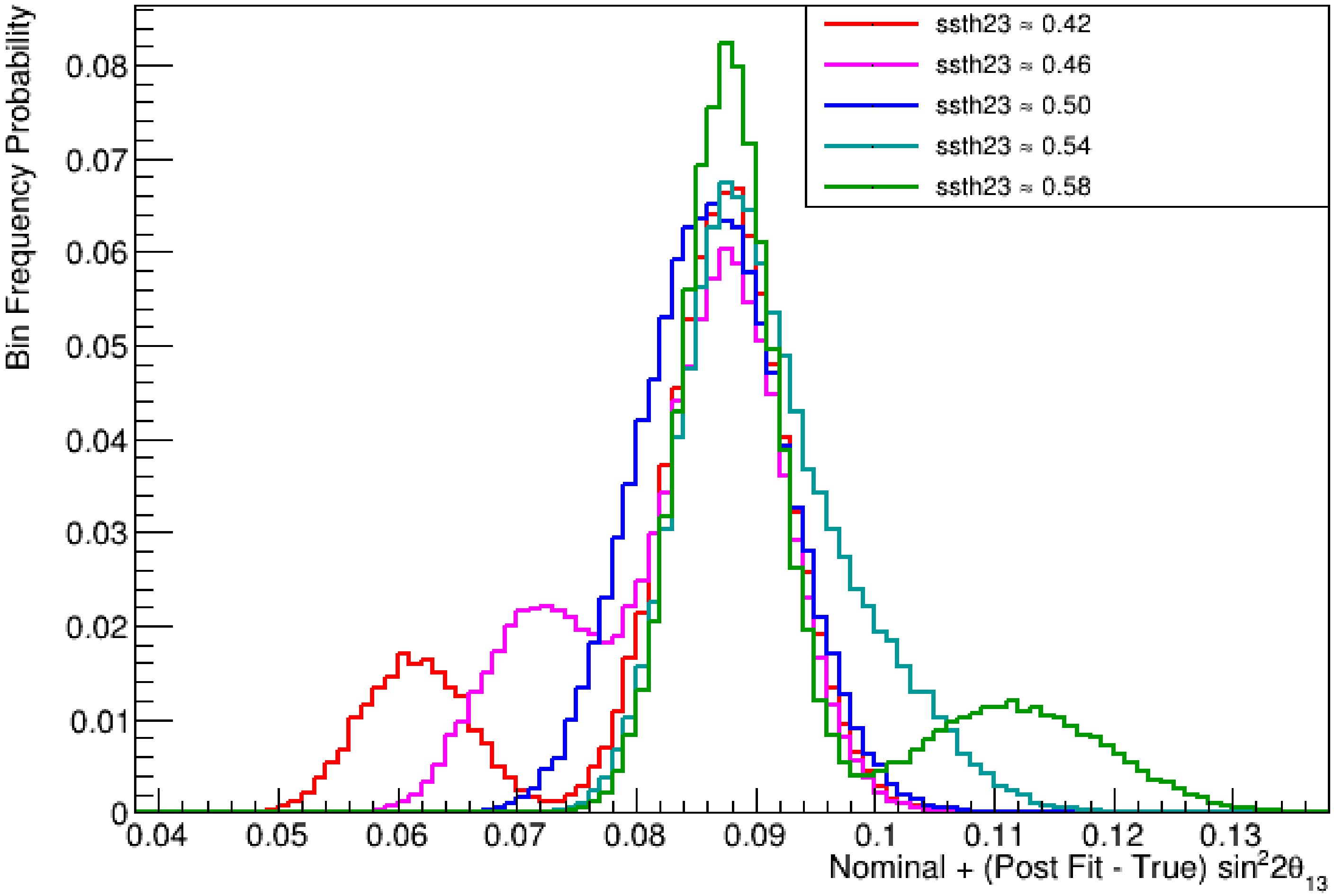
7 year exposure



15 year exposure

- $\sin^2 2\theta_{13}$ post fit distribution shown at fixed $\sin^2\theta_{23} \approx 0.58$.
- Underestimated $\sin^2\theta_{23}$ corresponds to overestimated $\sin^2 2\theta_{13}$, gap between modes due to disfavored maximal (~0.5) $\sin^2\theta_{23}$
- Increasing exposure decreases octant error significance

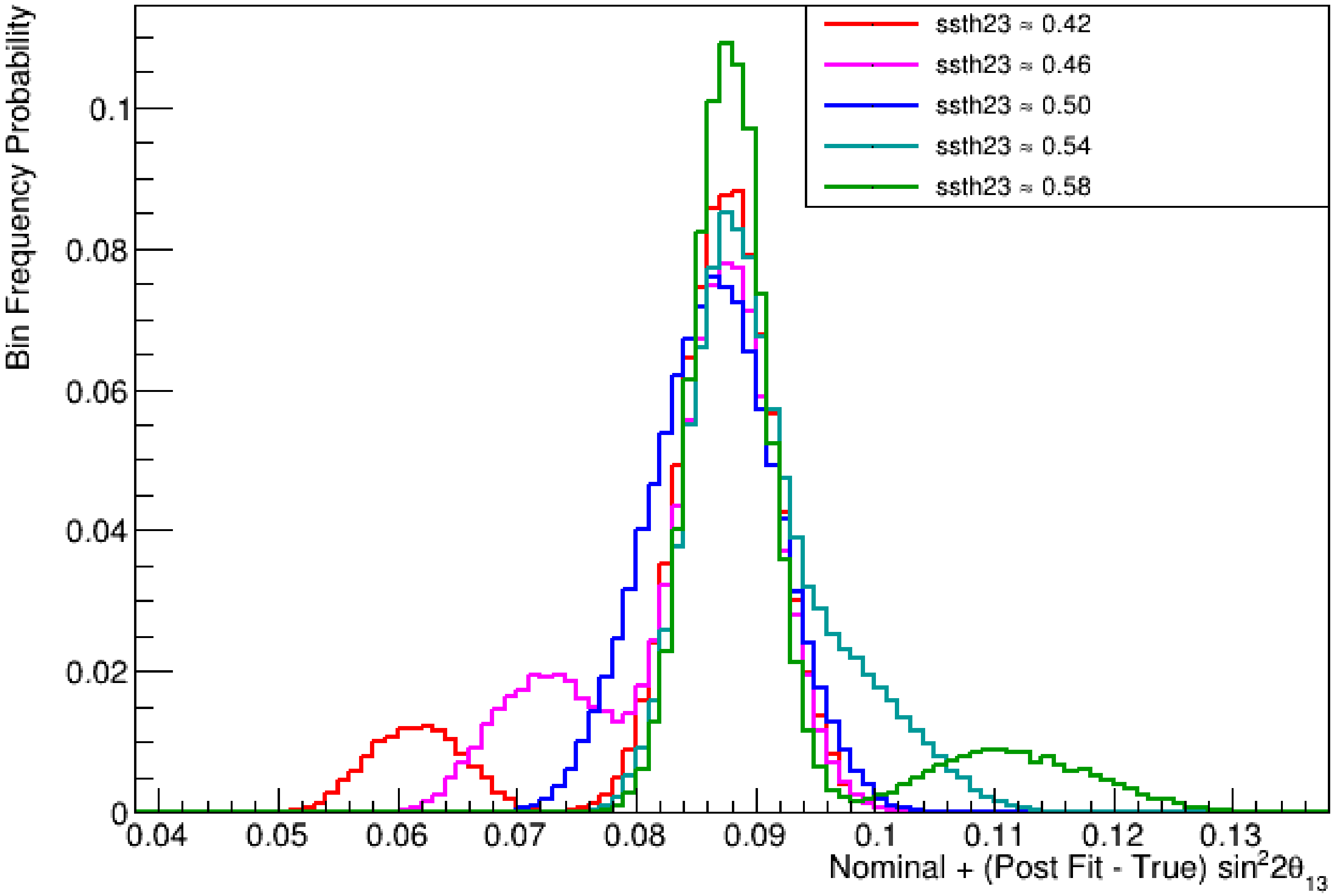
PF θ_{13} distribution depends on θ_{23}



7 year exposure

- Narrower true mode peak, greater true-error mode separation at non-maximal θ_{23}
- Broader true mode peak, no bimodality at maximal θ_{23}

PF θ_{13} distribution depends on θ_{23}

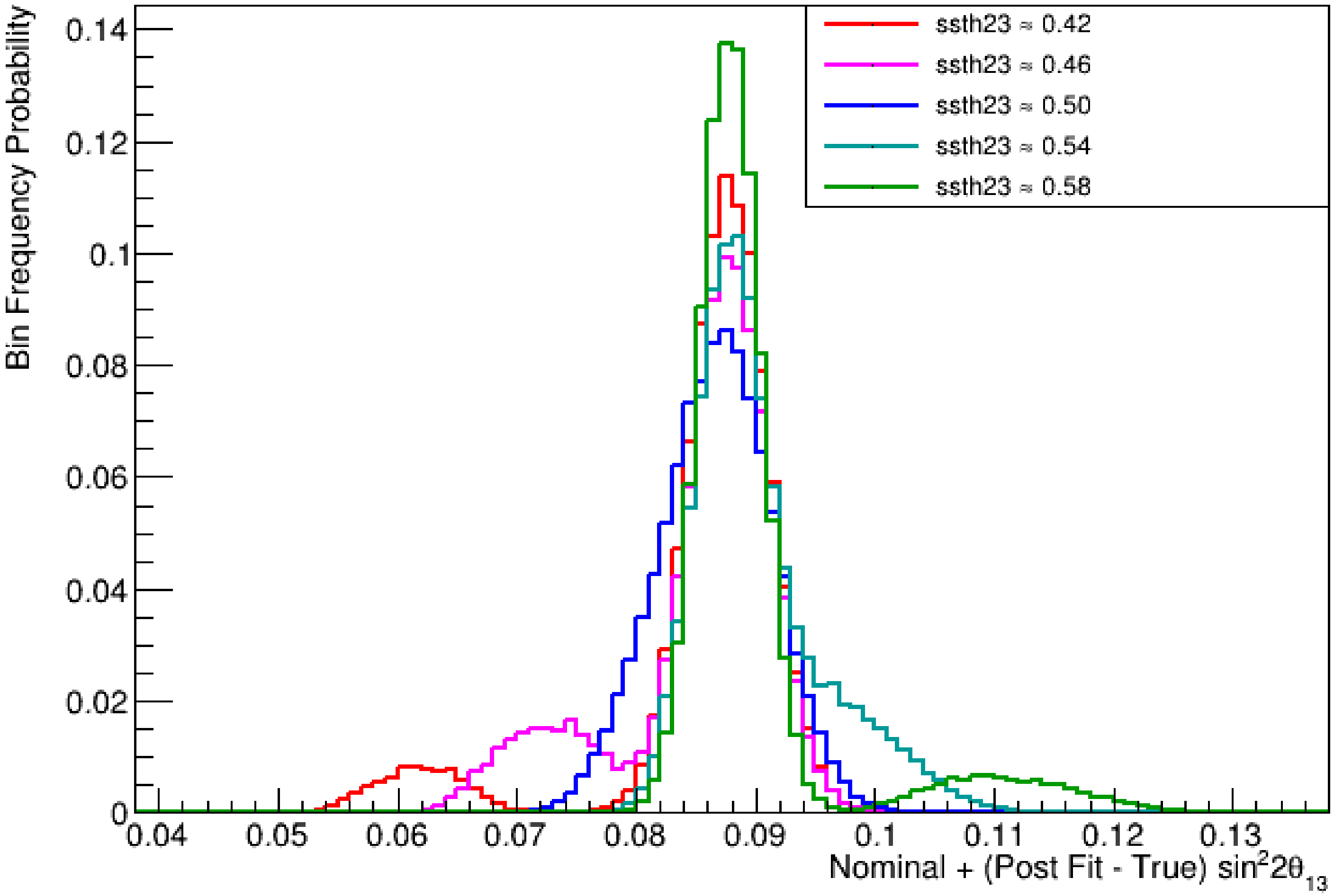


10 year exposure

Relative size of error mode decreases with exposure

- Narrower true mode peak, greater true-error mode separation at non-maximal θ_{23}
- Broader true mode peak, no bimodality at maximal θ_{23}

PF θ_{13} distribution depends on θ_{23}



15 year exposure

Relative size of error mode decreases with exposure

- Narrower true mode peak, greater true-error mode separation at non-maximal θ_{23}
- Broader true mode peak, no bimodality at maximal θ_{23}

New Physics? PMNS Non-unitarity

- PMNS matrix parameterized under assumption of unitarity
- Non-unitarity → More neutrino states → physics beyond SM
- If PMNS is non-unitary, θ_{13} becomes an effective mixing angle
  - Different measurements may yield different values
- **Comparing DUNE's precision θ_{13} measurement to Daya Bay's may amount to an indirect test of PMNS non-unitarity**

Neutrino Mixing

- Can parameterize PMNS matrix:

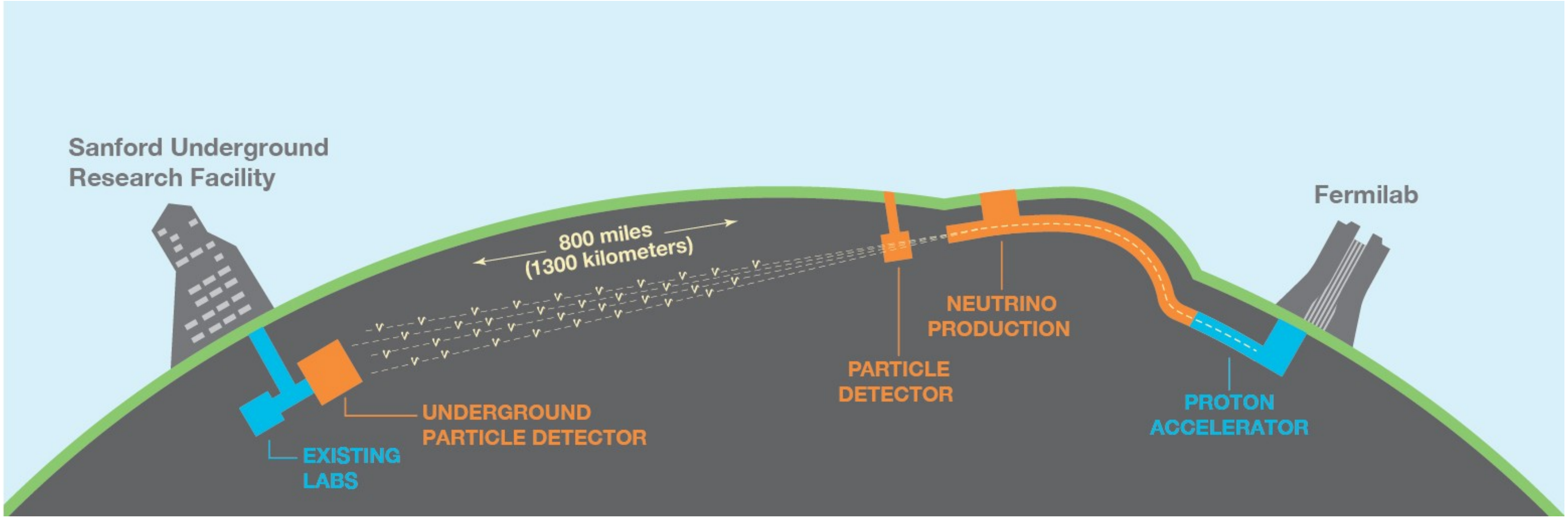
$$U_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\mathrm{I}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\mathrm{II}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathrm{III}}$$

- Unitarity means only three flavor/mass states
- Non-unitarity → new physics!
- DUNE (accelerator experiment) can measure blue highlighted parameters

Jeremy Fleishhacker

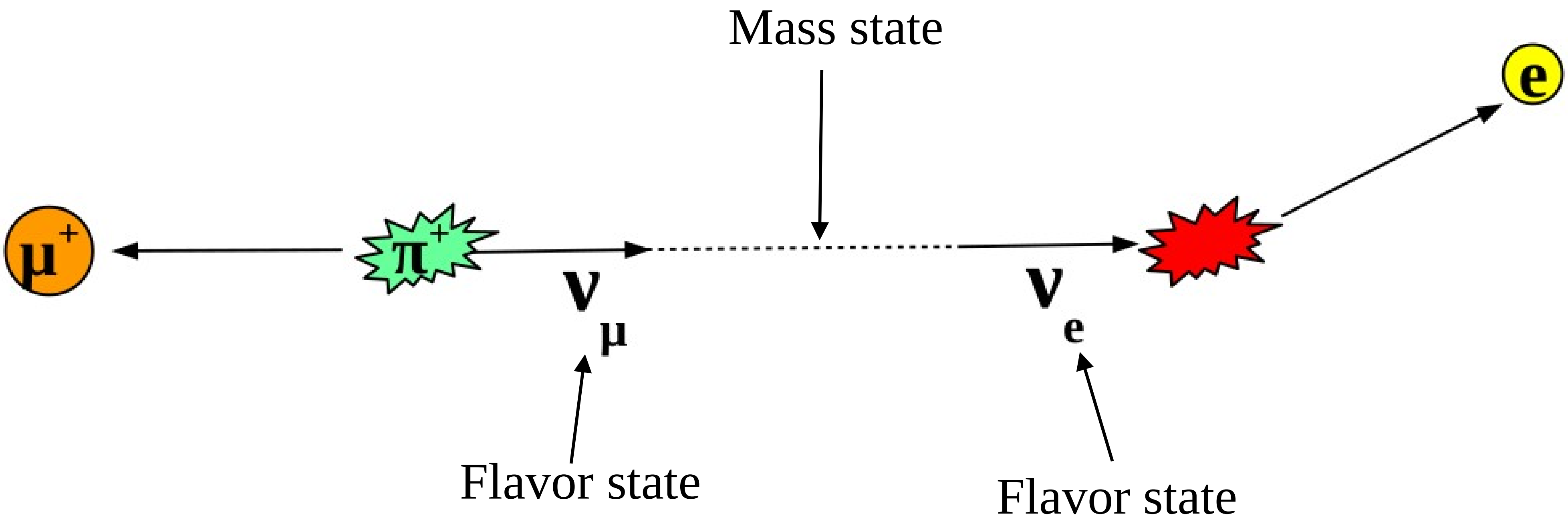
The DUNE Experiment

- **D**eep **U**nderground **N**eutrino **E**xperiment
- Large international collaboration aiming to make precise measurements of neutrino oscillation parameters
- Accelerator neutrino experiment with near and far detectors



Neutrino Oscillation/Mixing

- Neutrinos Mix! Created and destroyed in flavor states but propagate in mass states:



Neutrino Oscillation/Mixing

- Neutrinos Mix! Created and destroyed in flavor eigenstates but propagate in mass eigenstates
- Mixing described by PMNS Matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor States Mass States

The Mixing Matrix

- Can parameterize PMNS matrix:

$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{I}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{II}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{III}}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

- Assumes only three flavor/mass states

The Mixing Matrix

- Can parameterize PMNS matrix:

$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{I}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{II}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{III}}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

- Assumes only three flavor/mass states

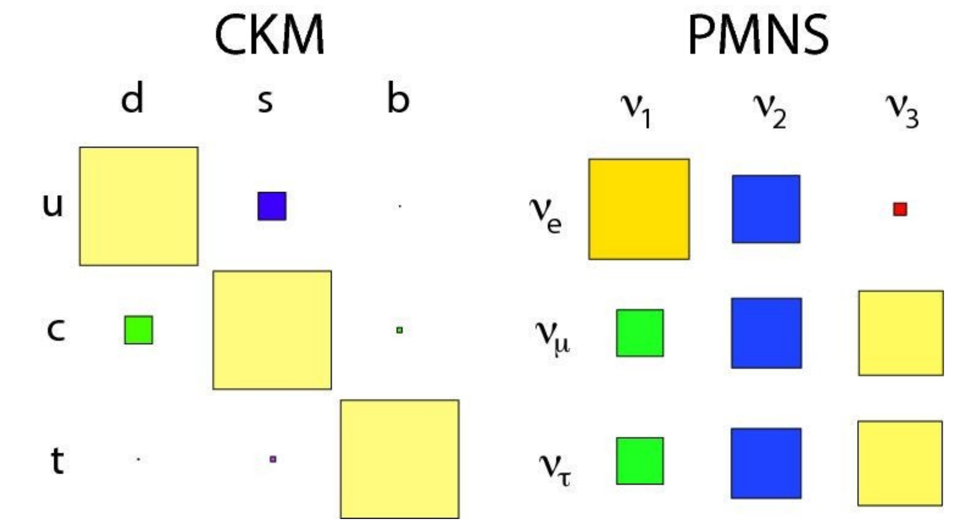
- **DUNE will measure θ_{13}, θ_{23}, δ_{CP}**

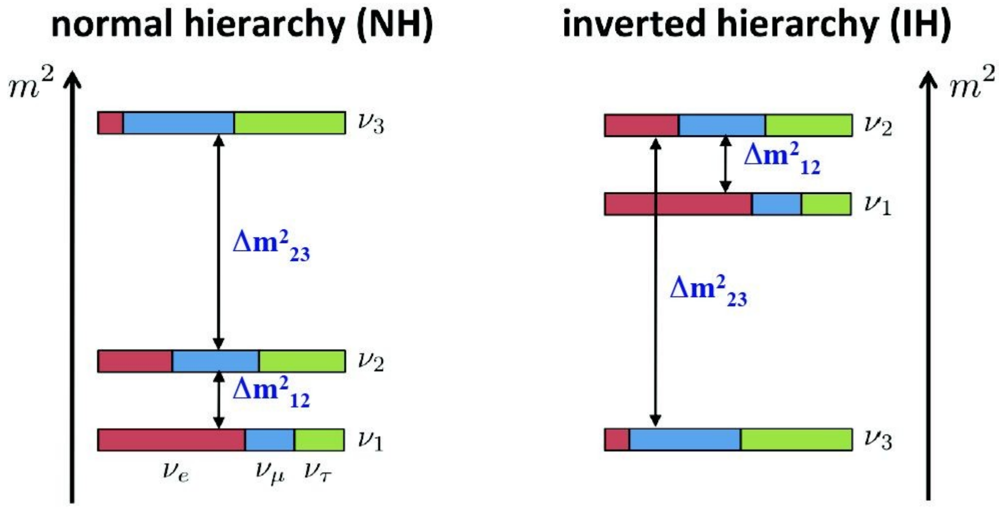
Why Measure δ_{CP}?

- δ_{CP} = charge-parity (CP) violation in lepton sector
- CP symmetry = invariant physics when mirroring space and reversing charge
- CP violation could explain matter-antimatter asymmetry
- Lepton CP violation not known

Why Measure θ_{13} and θ_{23}?

- Increase precision of PMNS element measurements
  - Why are CKM and PMNS matrices so different?
  - Is there a μ-τ mixing symmetry?
- Physics beyond the Standard Model





Jeremy Fleishhacker

Neutrino Oscillation Probabilities

- DUNE can't measure oscillation parameters directly
- Instead measures **oscillation probabilities**, which depend on the parameters in a complicated way:

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$

$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$

$$+\cos^2\theta_{23}\sin^2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

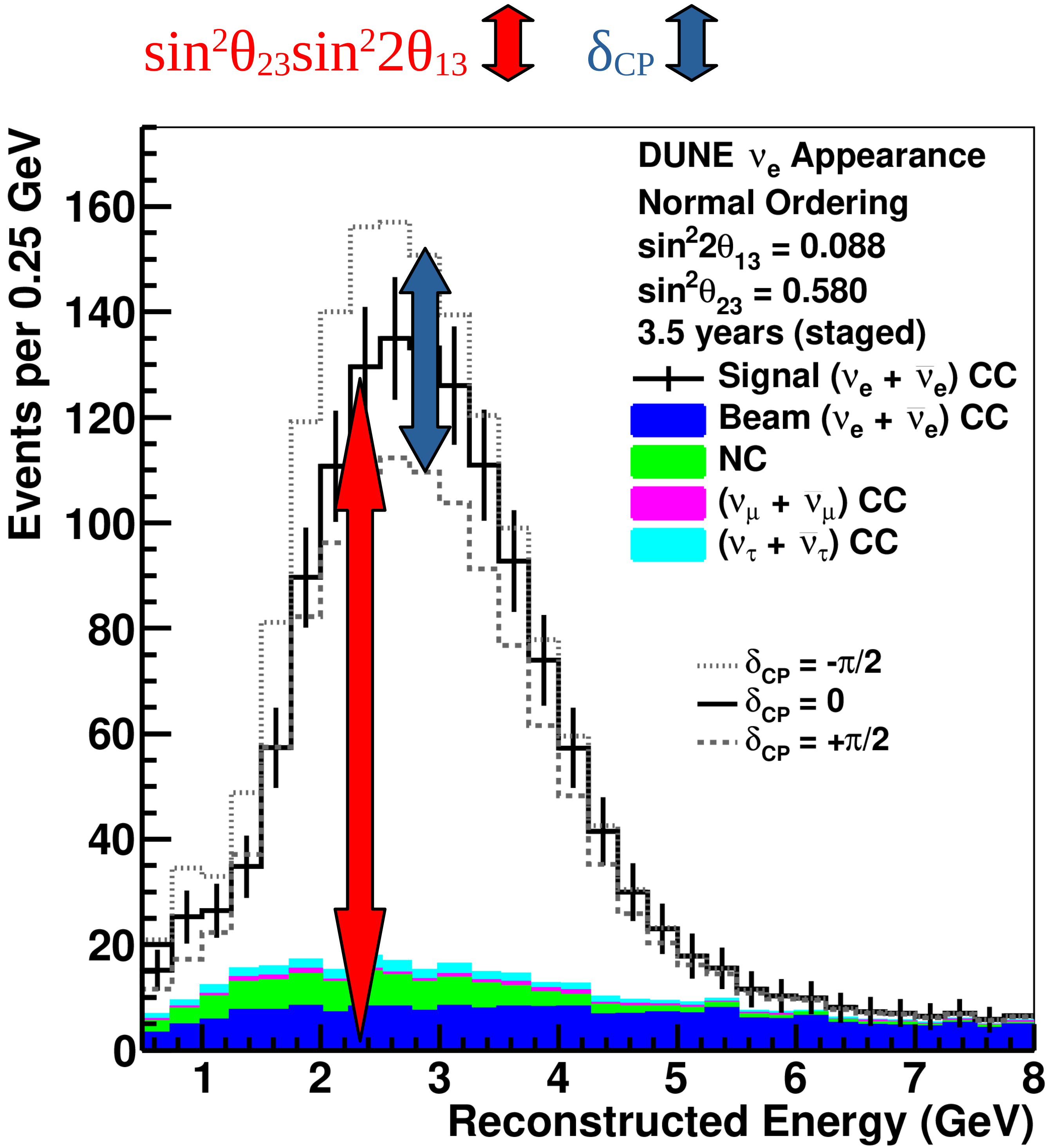
$$a = G_F N_e/\sqrt{2}$$

$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$

Neu... ...ies

- DUN... ...rectly
- Inste... ...h depe...

$P(\nu_\mu \rightarrow \nu_e)$ ... $\Delta_{31} + \delta_{CP})$ ... $\sqrt{2}$ ... $/4E_\nu$

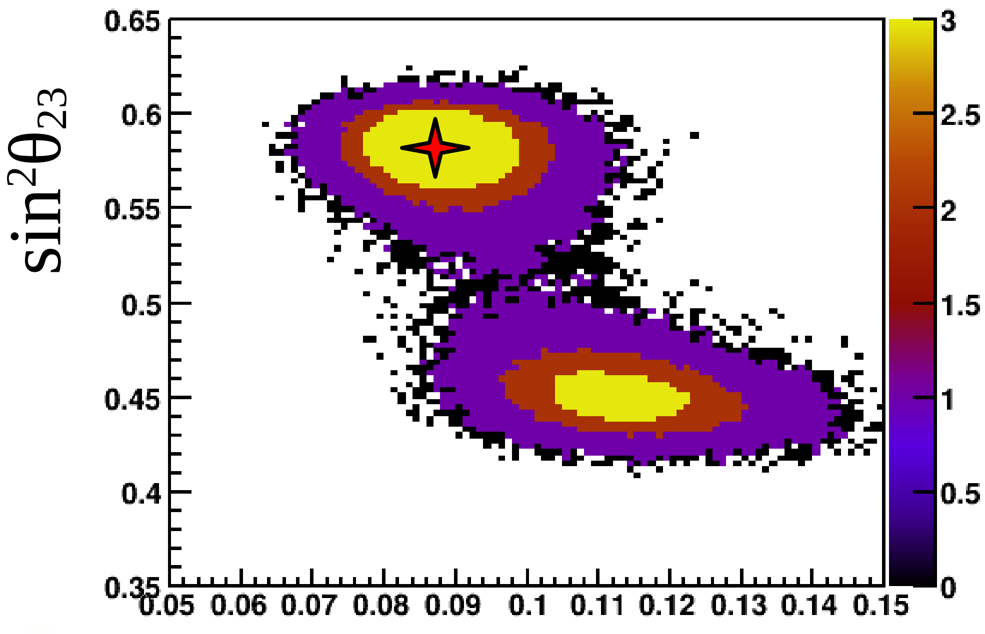


Asimov Studies

- Fix "Asimov" point of true parameters
- All systematics nominal, exposure 1000 ktMWyrs
- Pick up to two parameters to "scan" (fix away from their true values) and calculate the scan χ^2 at each scan point
- Take the difference between the scan χ^2 and the global χ^2 to find $\Delta\chi^2$ and calculate confidence intervals

Neutrino Oscillation Probabilities

- Complicated parameter dependencies lead to **degeneracies** and **correlations**
  - e.g. θ_{13}-θ_{23} correlation resulting from leading term dependence



$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$a = G_F N_e/\sqrt{2}$$
$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$

Sources of Degeneracy

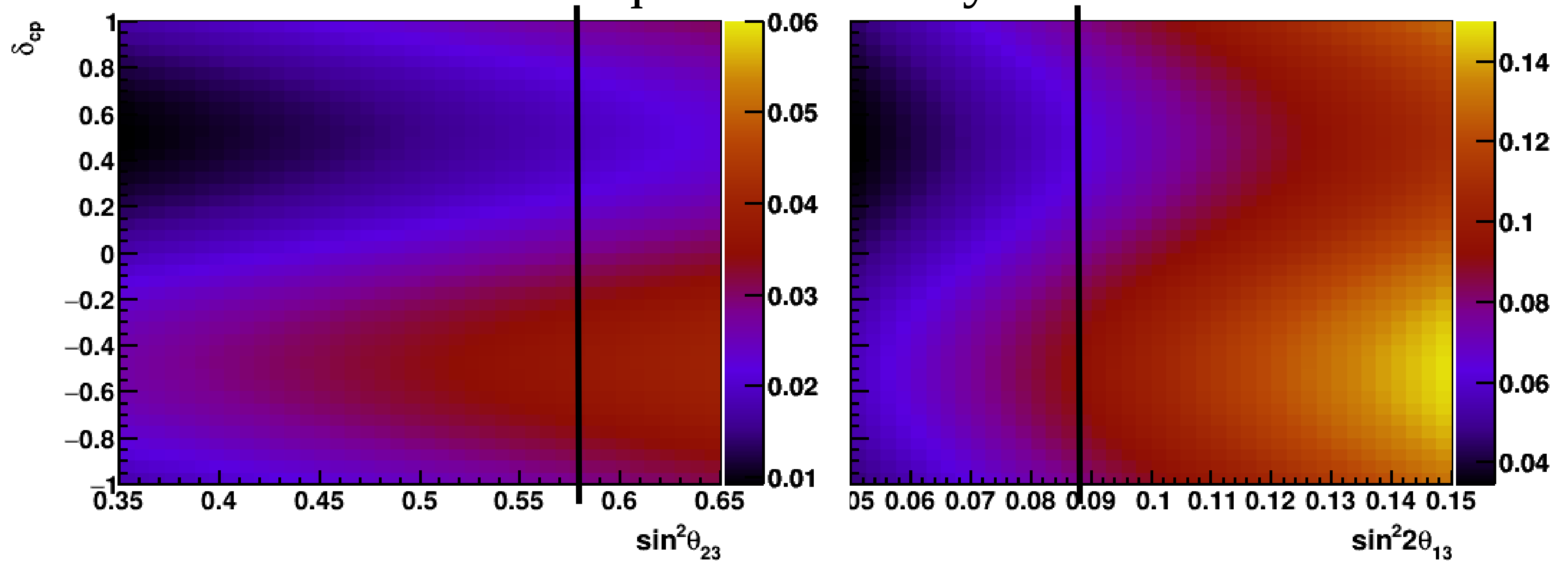
- θ_{13}-θ_{23}: ν_e appearance dependence on product $\sin^2\theta_{23}\sin^2 2\theta_{13}$ leads to anti-correlation
  - ν_μ constraint on $\sin^2 2\theta_{23}$ not $\sin^2\theta_{23}$ (for low θ_{13})

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times (1-\cos^2\theta_{13}\sin^2\theta_{23}) \times \sin^2\Delta_{atm} \approx 1 - \sin^2 2\theta_{23}\sin^2\Delta_{atm}$$

- δ_{CP}: sine dependence at flux peak ($\Delta_{31}=\pi/2$)

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

Contours of Equal Probability at Flux Peak



- δ_{CP}: sine dependence at flux peak ($\Delta_{31}=\pi/2$)

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$