A third TDR-era paper: deep dive into θ_{13}, θ_{23}, δ_{CP} and parameter degeneracies

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$P(\nu_\mu \rightarrow \nu_e)$ depends on four parameters in a complicated way

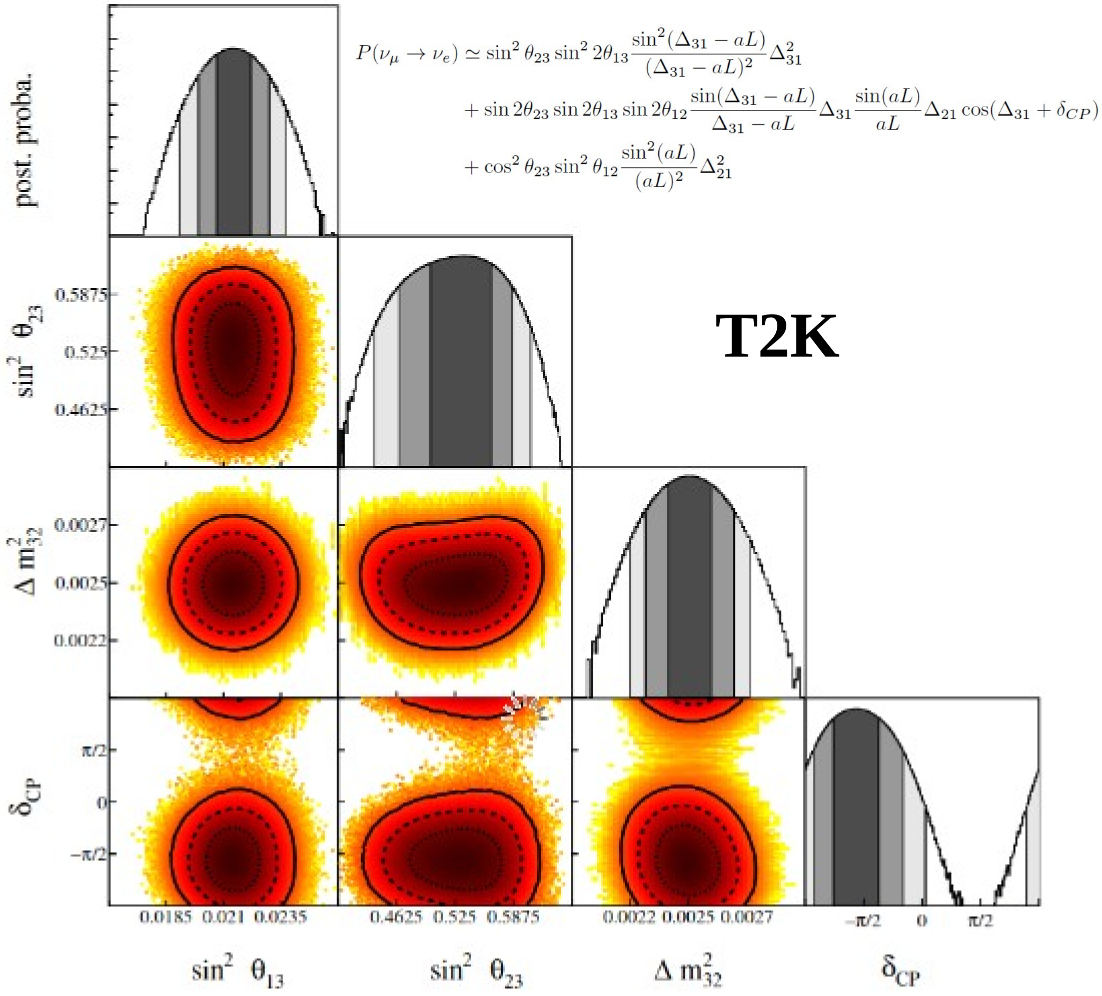
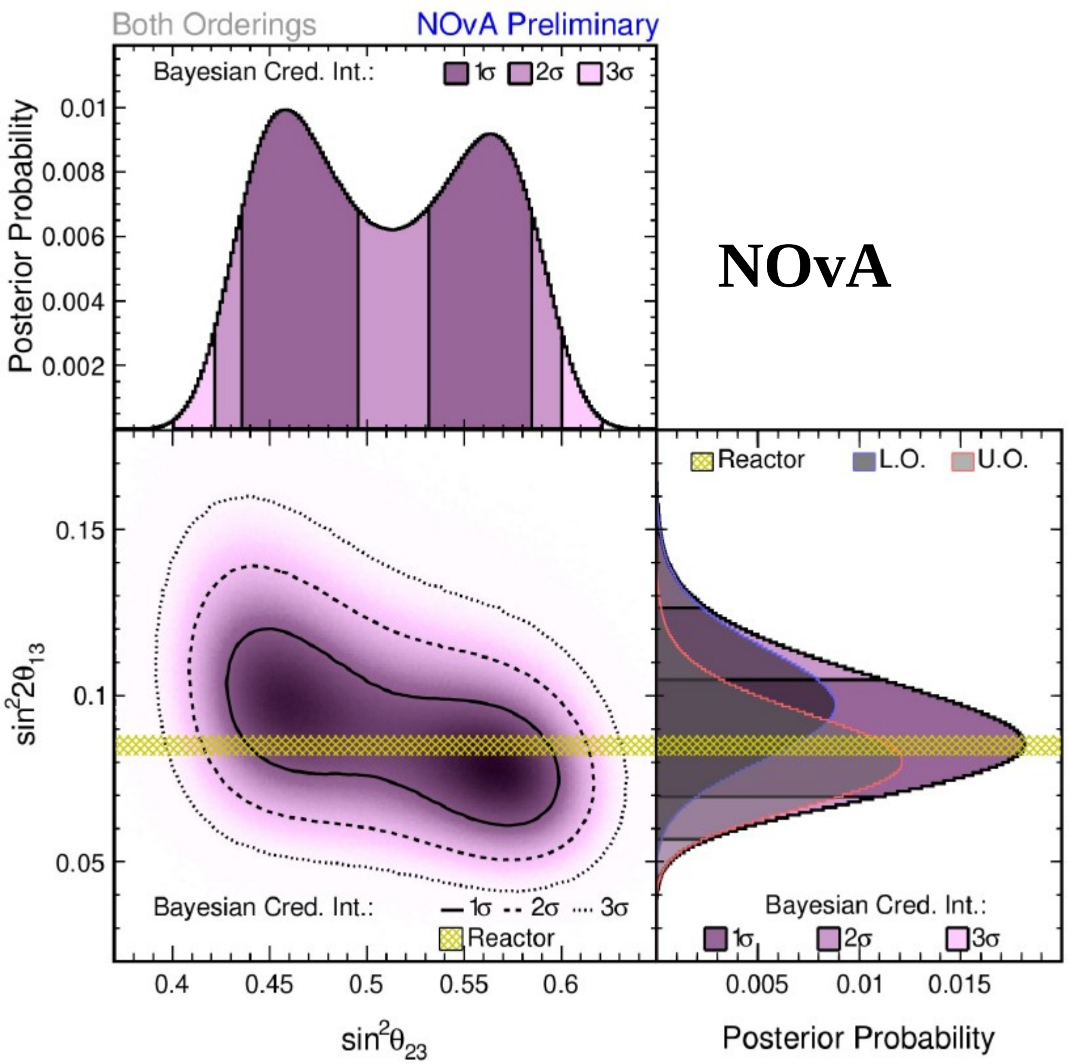


FIG. 64: Posteriors probabilities together with 1, 2 and 3 σ credible intervals for all the oscillation parameters of interest and their combinations in the normal mass ordering. A logarithmic scale is used for the axis corresponding to the posterior probability density, and darker colors correspond to larger probabilities.

- Three major open questions in neutrino oscillations can be addressed by measuring $\nu_\mu \rightarrow \nu_e$ transitions
  - CP violation (δ_{CP})
  - Mass ordering
  - θ_{23} octant
- These can be measured with accelerator (NOvA, T2K, T2HK, DUNE) and atmospheric (IceCUBE, SK, HK, km3net) neutrinos
- All of these experiments measure something that is sensitive to four parameters (θ_{13}, θ_{23}, δ_{CP}, Δm^2_{atm}) in a complicated way
- All measurements are actually allowed regions in this 4D parameter space, which can then be projected down to 1 or 2 parameters

There are several places where allowed regions can be disjoint



NOvA

- To leading order, experiments are sensitive to the product $\sin^2 2\theta_{13}\sin^2\theta_{23}$, so it is common for these parameters to be highly correlated in fits
- ν_μ disappearance constrains $\sin^2 2\theta_{23}$; when it is non-maximal, postfit probability density distributions become bimodal
- This makes it especially challenging for appearance experiments to measure θ_{13}

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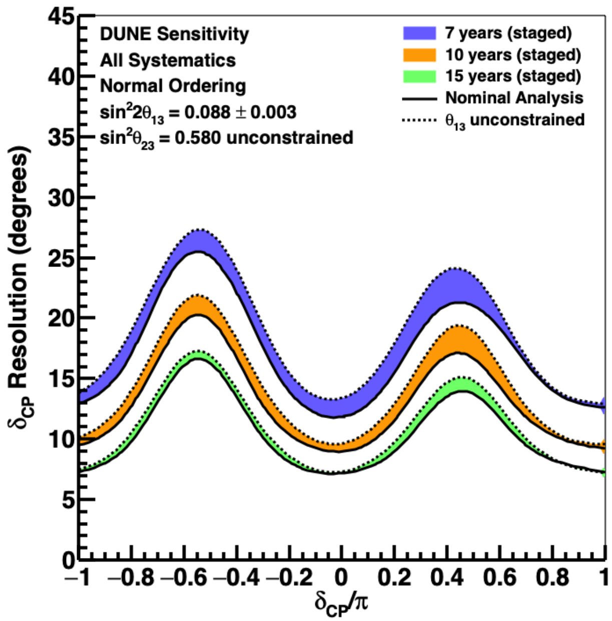
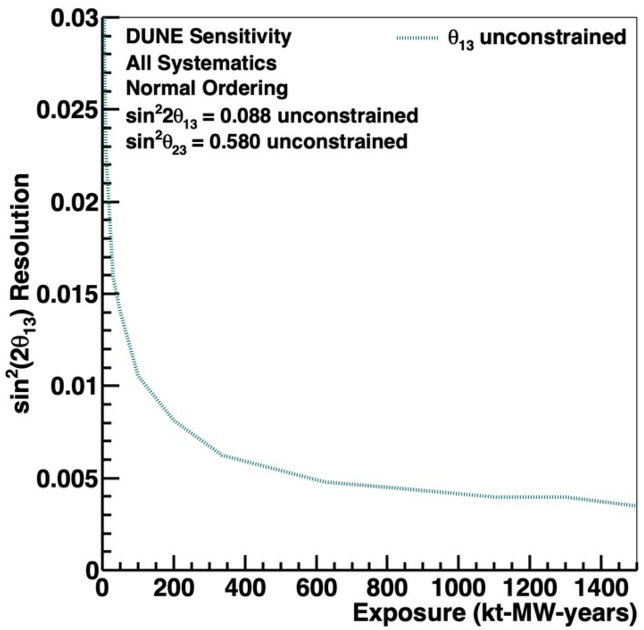
What is “resolution” when there are disjoint allowed regions?





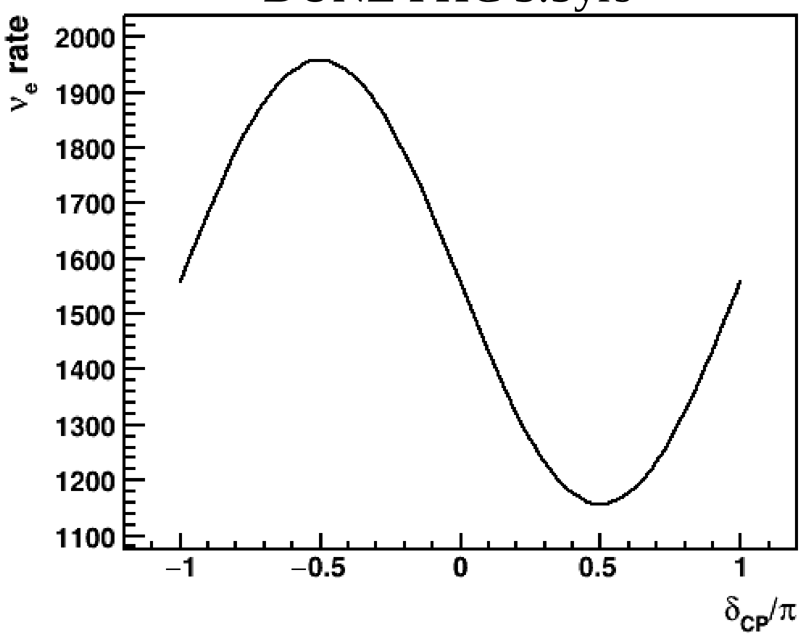
- One can define a parameter resolution as the width of the 68% allowed region, or the width of the $\Delta\chi^2 < 1$ region, but it’s not obvious what to do when there are two disconnected regions
- This happened not to be a problem for us at 68%, but it is a problem at 90%

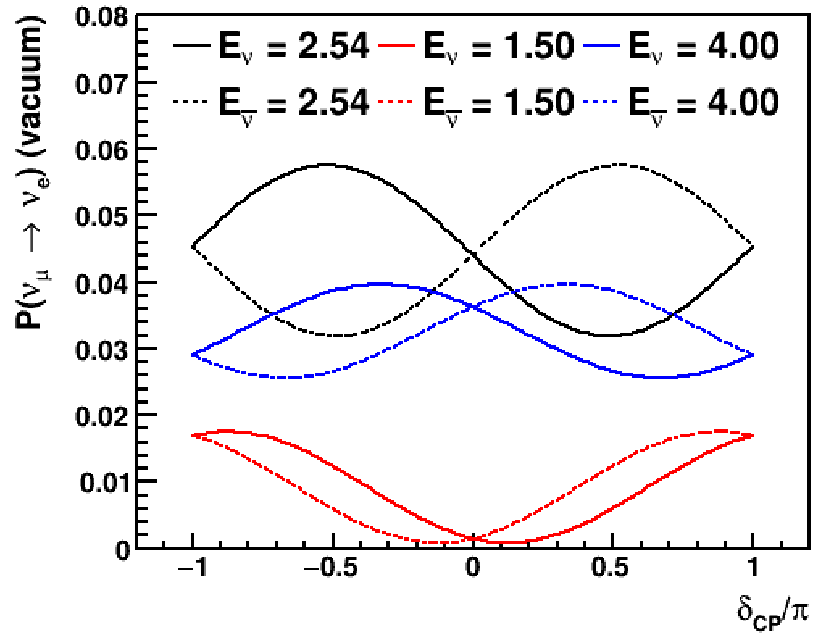
Example: the "sinδ degeneracy"

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

π/2 at flux peak

DUNE FHC 3.5yrs





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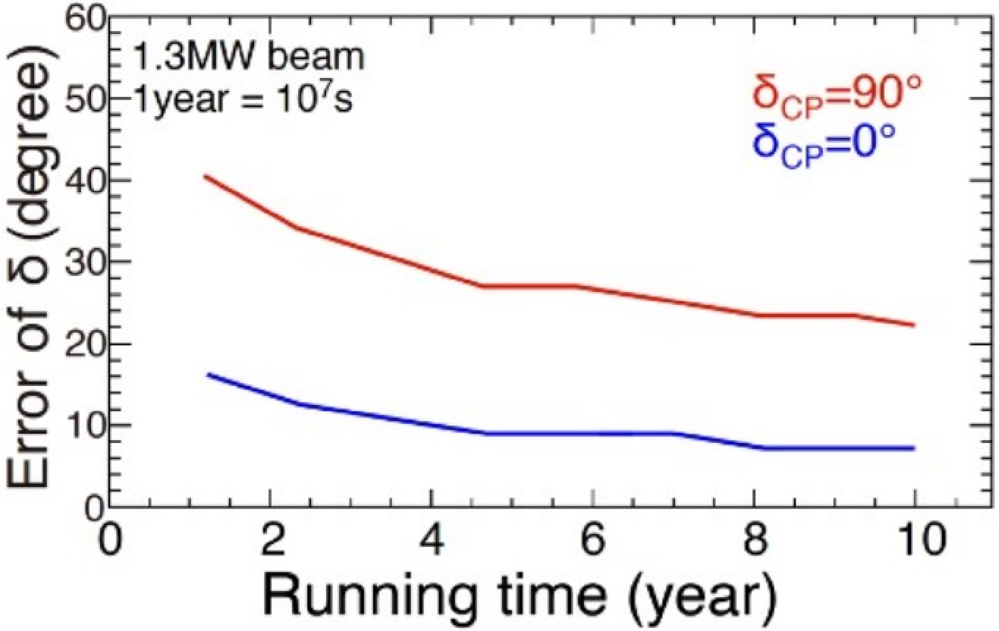
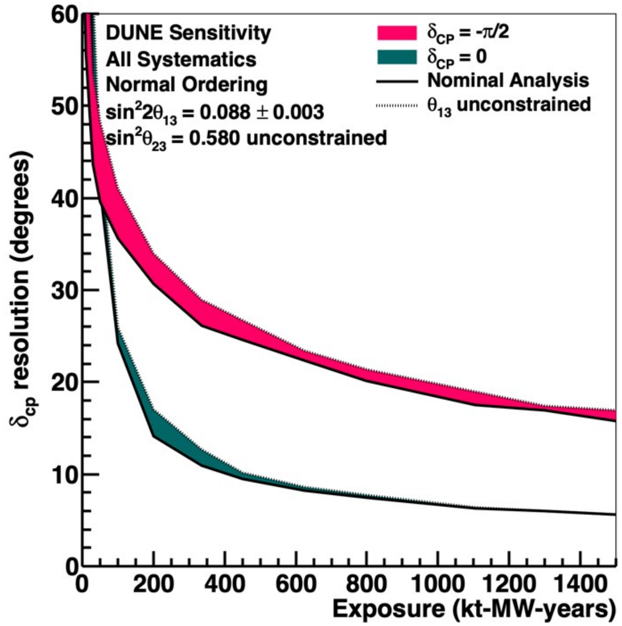
By focusing on 0° and 90°, we are sidestepping this issue

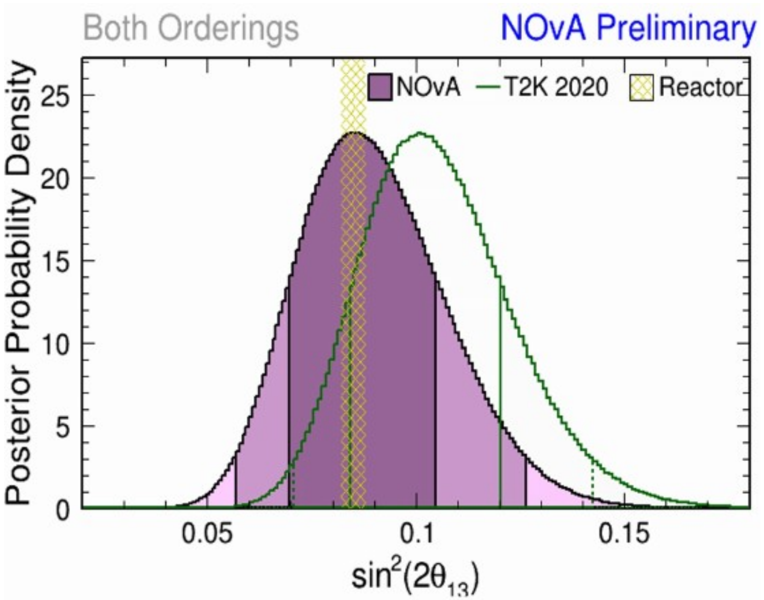


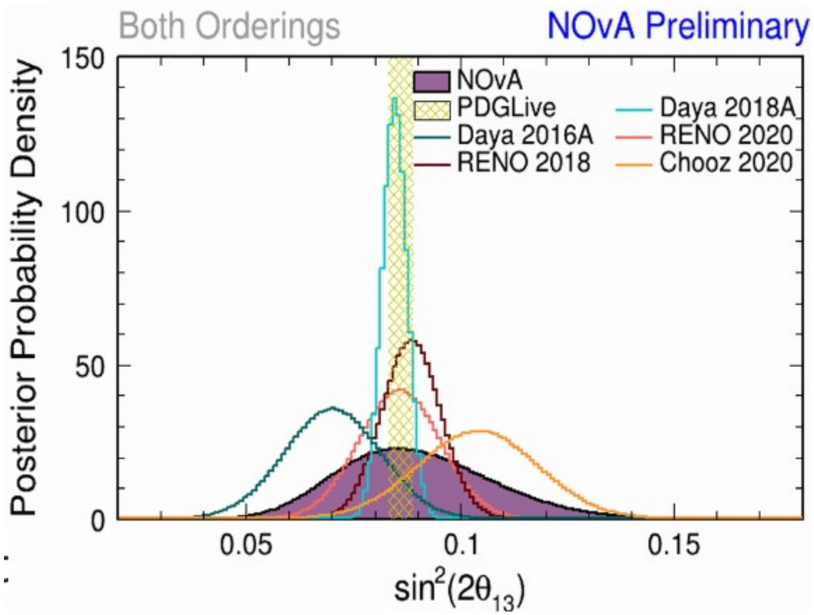


- DUNE has slightly better δ resolution than T2HK at 0 and 90, which are the points where shape matters the least
- I strongly suspect that T2HK has almost no ability to distinguish 45° from 135°, whereas DUNE can
- T2HK has never said what "error of δ" means, or shown any plots of resolutions at other true values of δ (this issue doesn't affect CPV significance)
- It is likely that δ is not a multiple of π/2, and it is bad for DUNE/T2HK comparisons that the conversation is so focused on maximal CPV

θ_{13}: cross check and non-unitarity

- DUNE has ~0.004 resolution to $\sin^2 2\theta_{13}$, which is roughly twice as good as T2HK reports
- Daya Bay resolution is 0.003, and has no meaningful cross-check currently (other measurements are ~10x worse)
- A deviation between θ_{13} from appearance and disappearance would be indirect evidence of PMNS non-unitarity → DUNE is the best way to do this





Proposal

- Choose a few especially challenging true oscillation points (NO, lower octant, $\delta \sim -\pi/4$?) to run a large number of throws, and look at the 3D or 4D distribution of best fit values
- Look at the 1σ-90%-3σ allowed regions for δ, θ_{13}, θ_{23}; at least the 90% and 3σ will have tricky correlations
- Look at DUNE-Daya Bay non-unitarity test for different values of θ_{23}, for what region(s) of parameter space are we sensitive to non-unitarity
- I think this could make a third paper where we purposely seek out the hard regions and show how DUNE's spectral information ultimately resolves them

A little about me

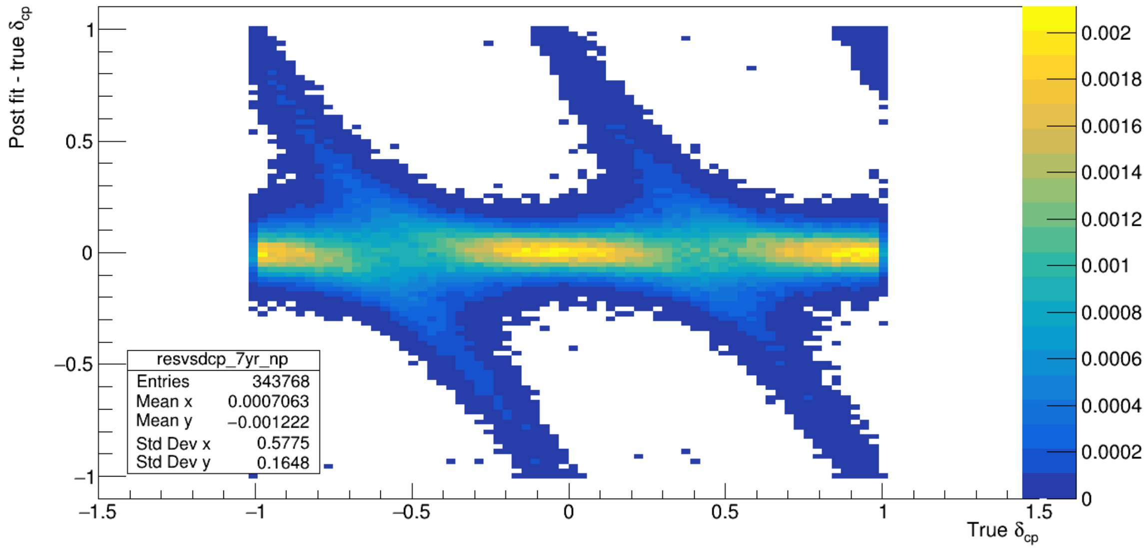
- Undergraduate student at Carleton College, MN
- REU student at the University of Rochester
- Previously worked with the NSD neutrino group at Berkeley Lab

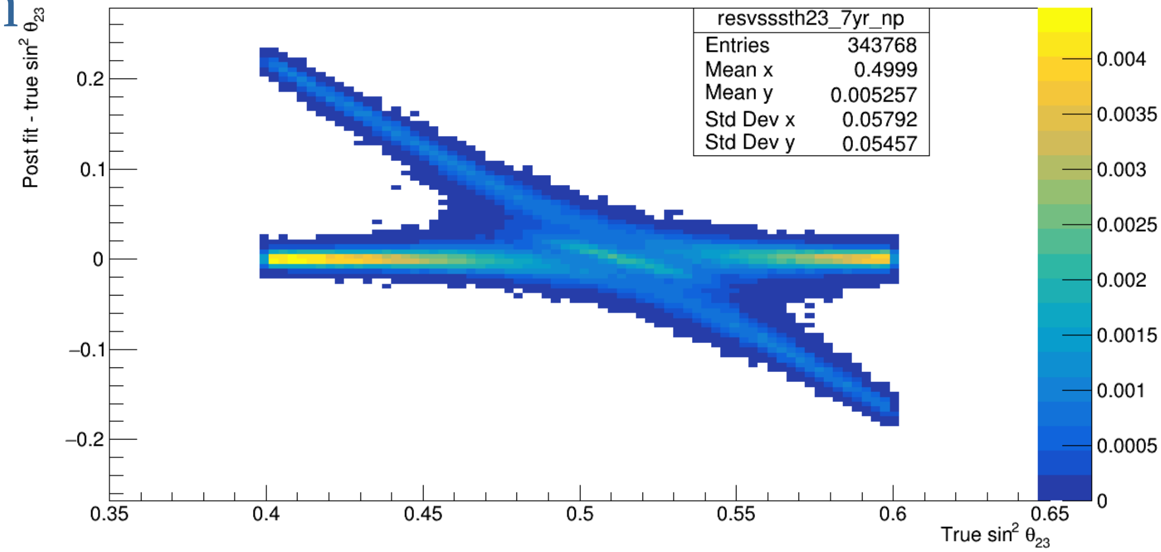
Why this study?

- Previous measurements of oscillation parameters have been treated independently, omitting possible correlations.
- As we develop the next generation of precision neutrino experiments, including DUNE, these correlations become significant
- Understanding how DUNE fits of oscillation parameters are affected by these correlations enables more accurate evaluation of DUNE's sensitivity to new physics.

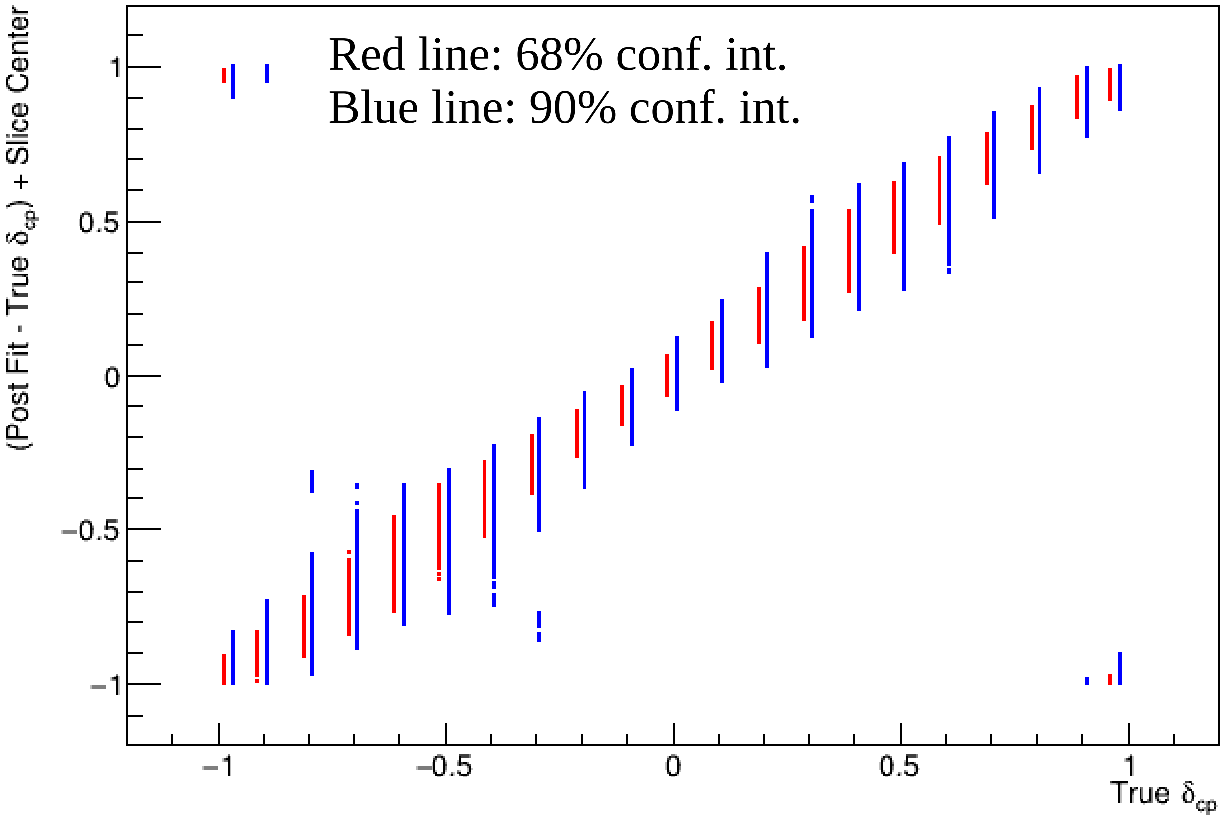
Initial TDR Analysis

- Resolution plots using LBL TDR analysis data.
- TOP: δ_{cp} post fit (pf) – true vs true
  - Sine dependence at flux peak---high precision at minimal cp violation, with 0-π octant degeneracy
- BOTTOM: $\sin^2\theta_{23}$ pf – true vs true
  - Octant flip at non-maximal mixing



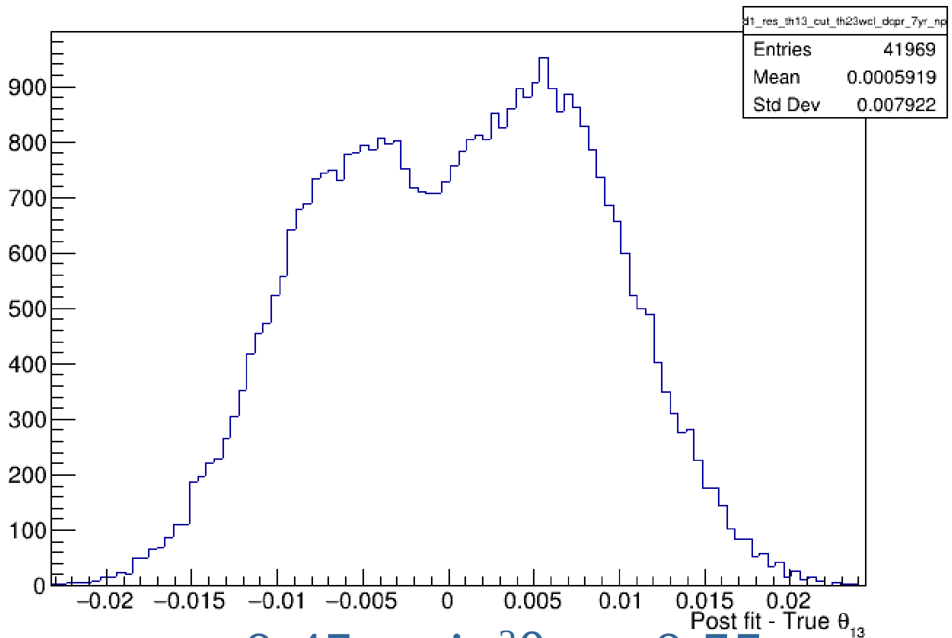


δ_{cp} octant degeneracy

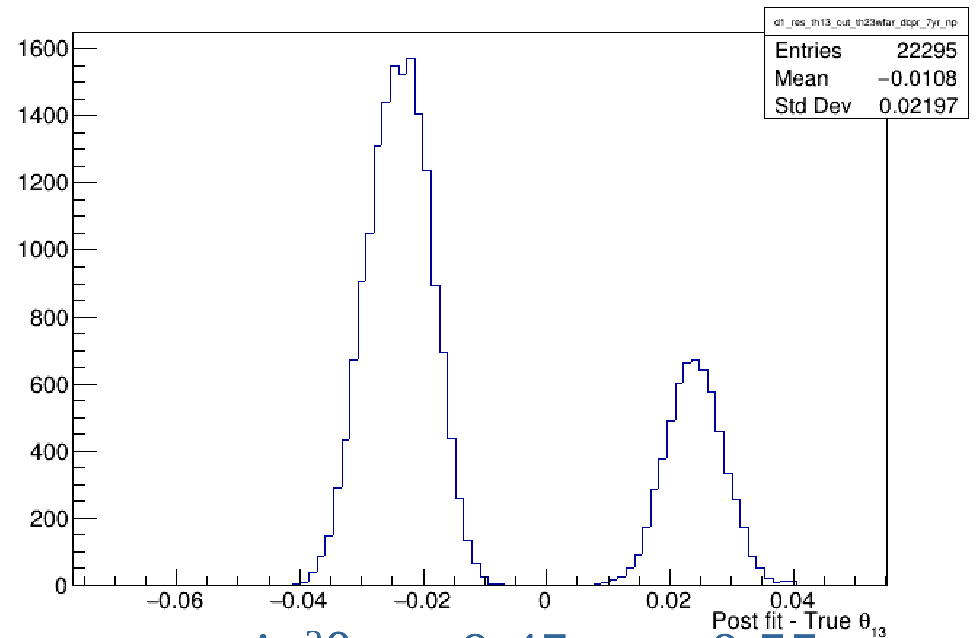


- $\nu_\mu \rightarrow \nu_e$ oscillation eqn has sine dependence on δ_{cp} (at flux peak)
  - Higher precision at minimal cp violation (-π, 0, π.)
  - Octant degeneracy
- 90% confidence interval captures degeneracy
  - Interval asymmetry about δ_{cp} slice value
- Octant asymmetry about $\delta_{cp} = 0$

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?

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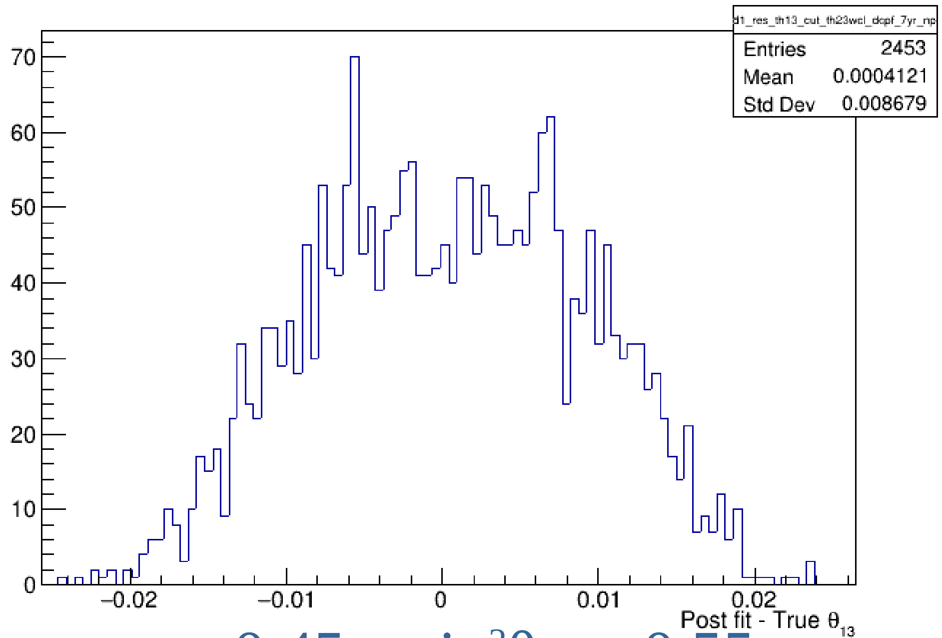
δ_{cp} effect?



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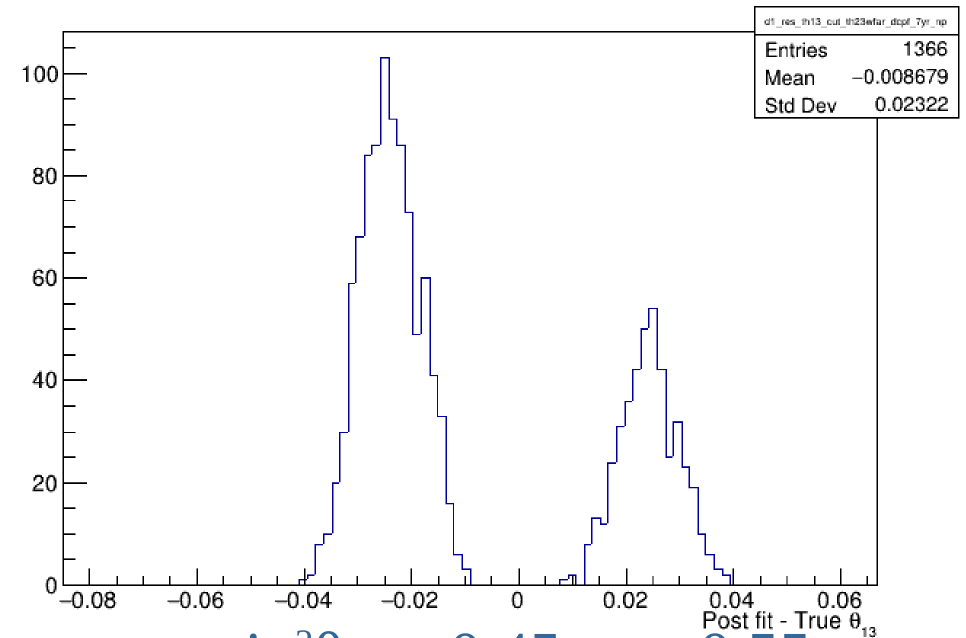
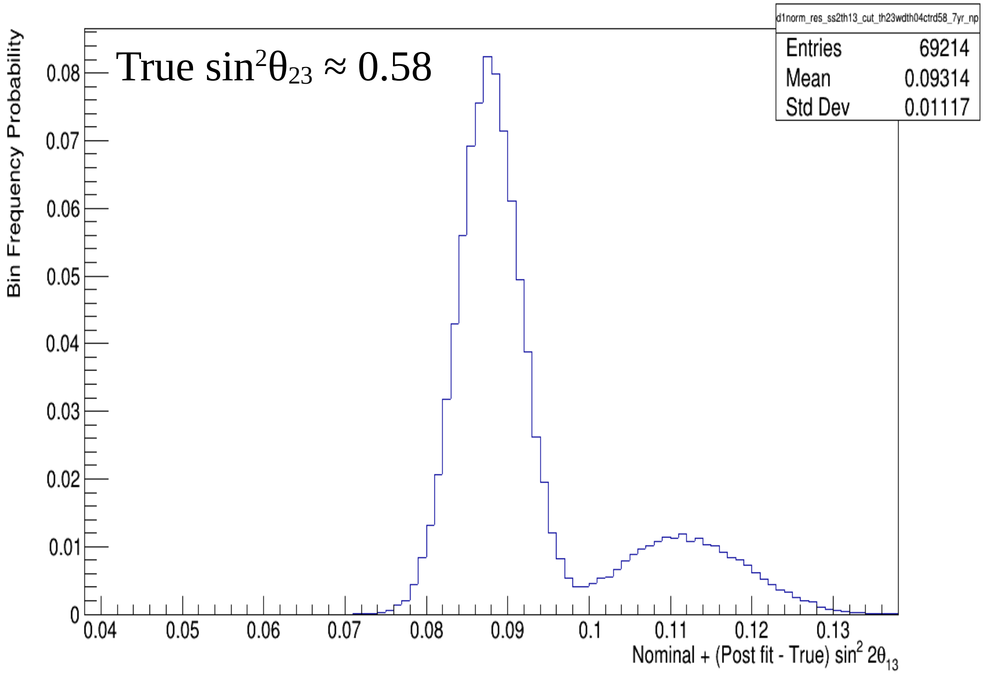


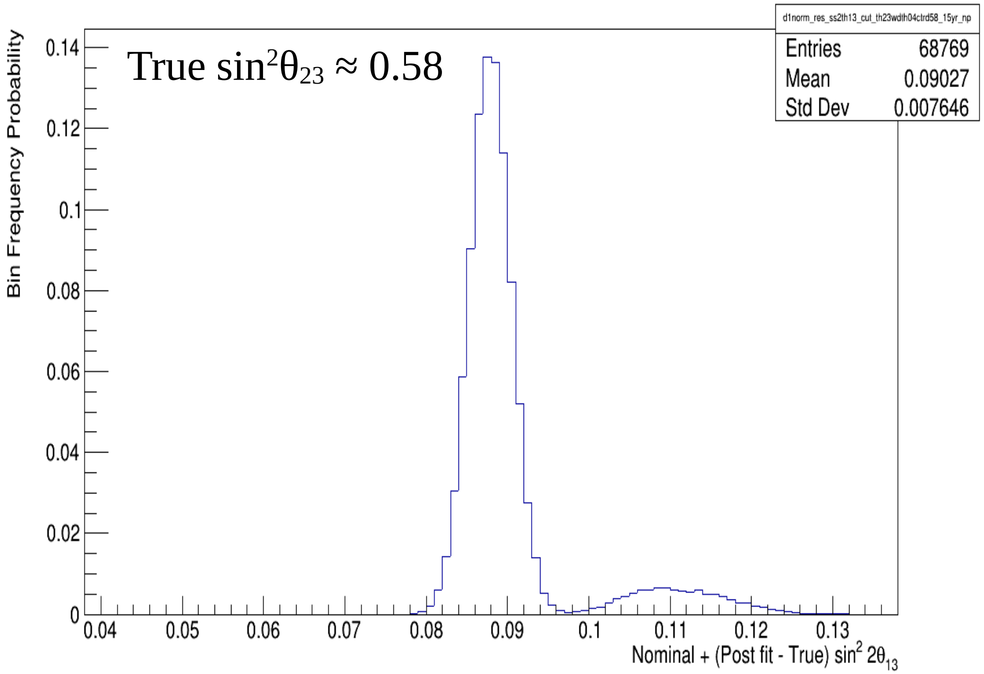
$\sin^2\theta_{23} < 0.45$ or > 0.55

- 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}



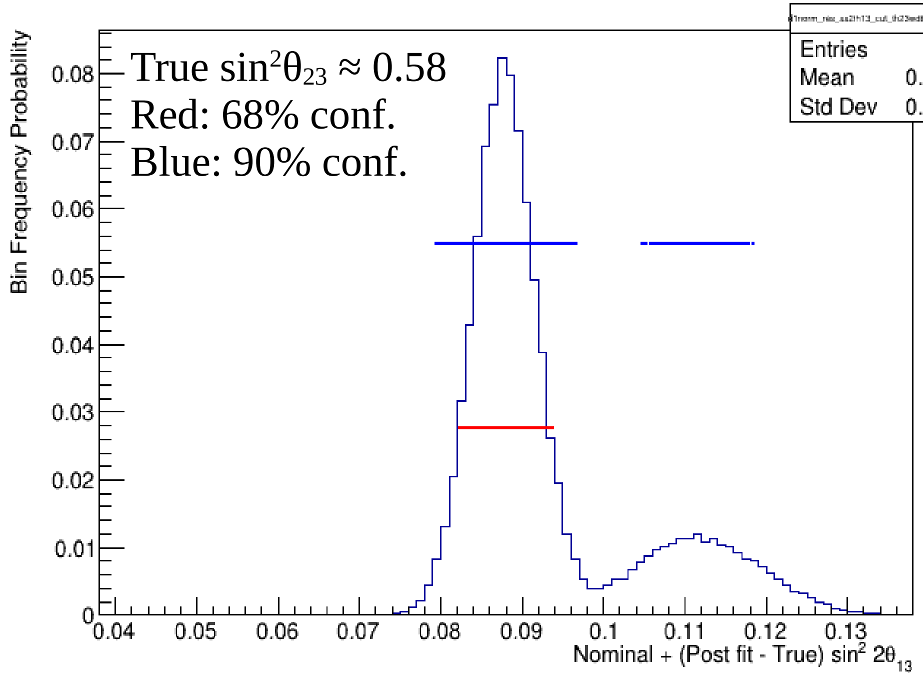
7 year exposure



15 year exposure

- $\sin^2 2\theta_{13}$ postfit 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}



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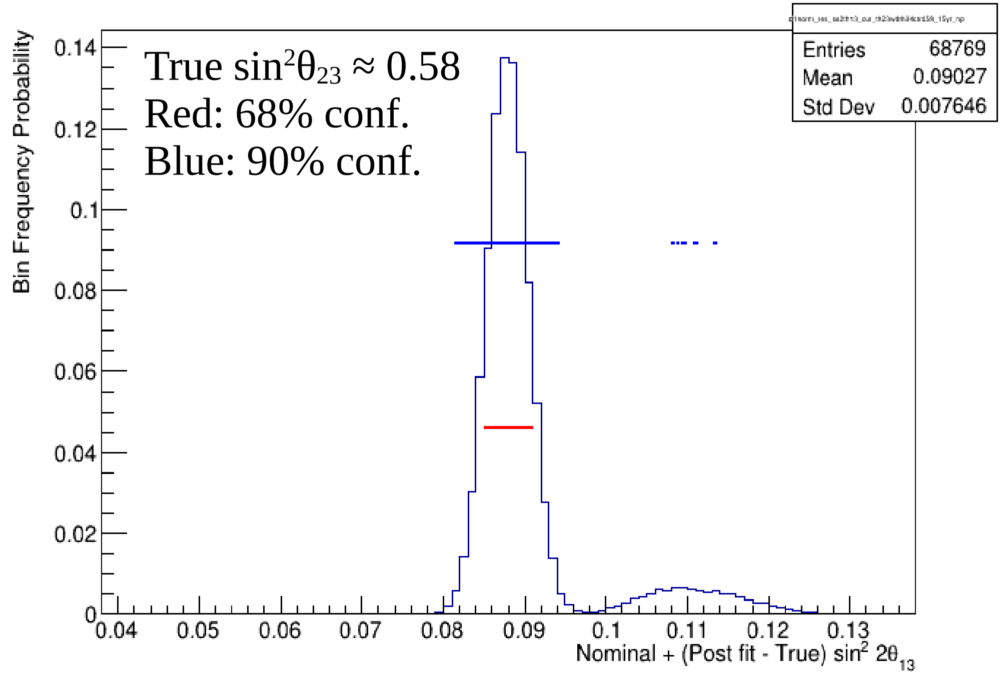

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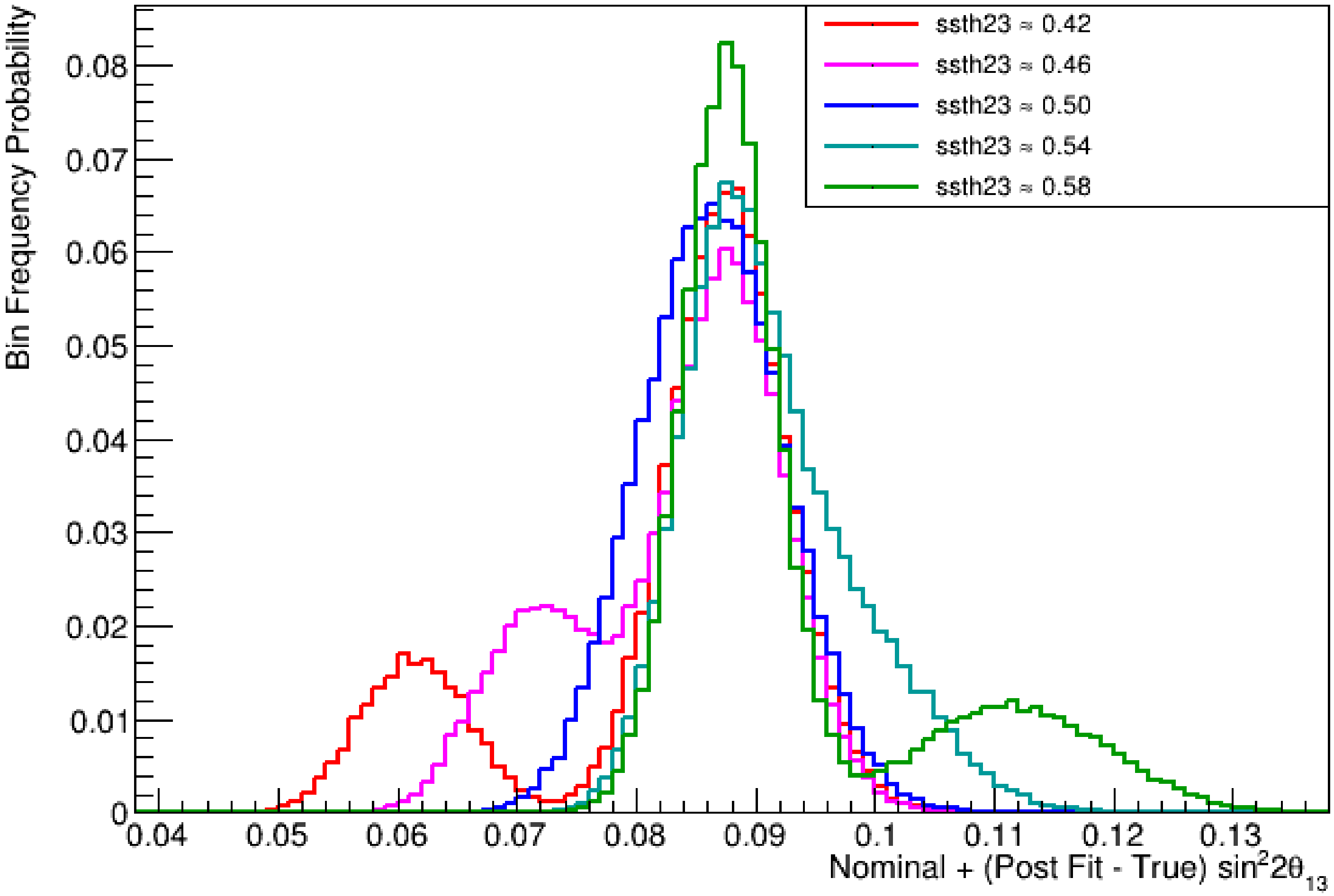
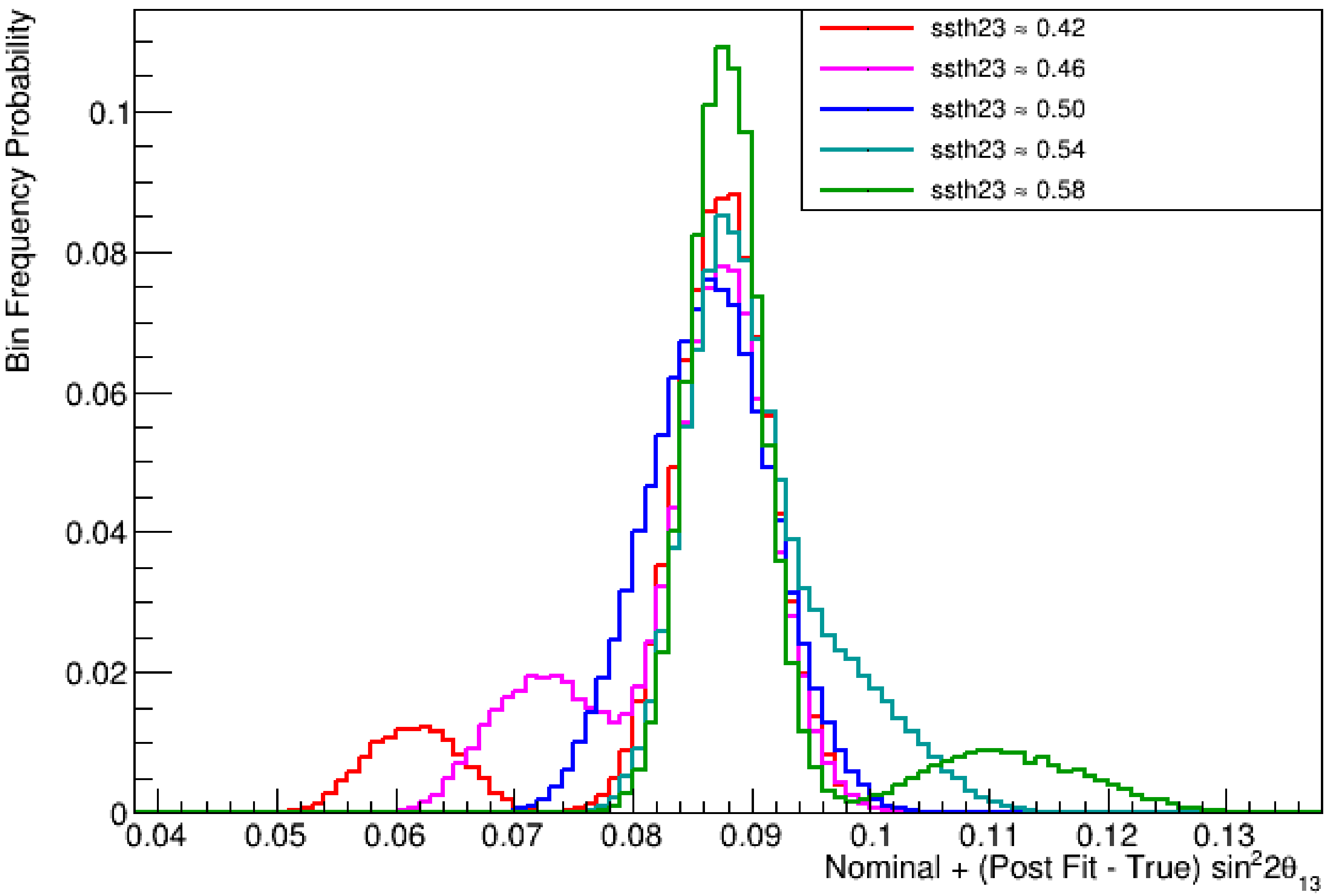
PF θ_{13} distribution depends on θ_{23}



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}

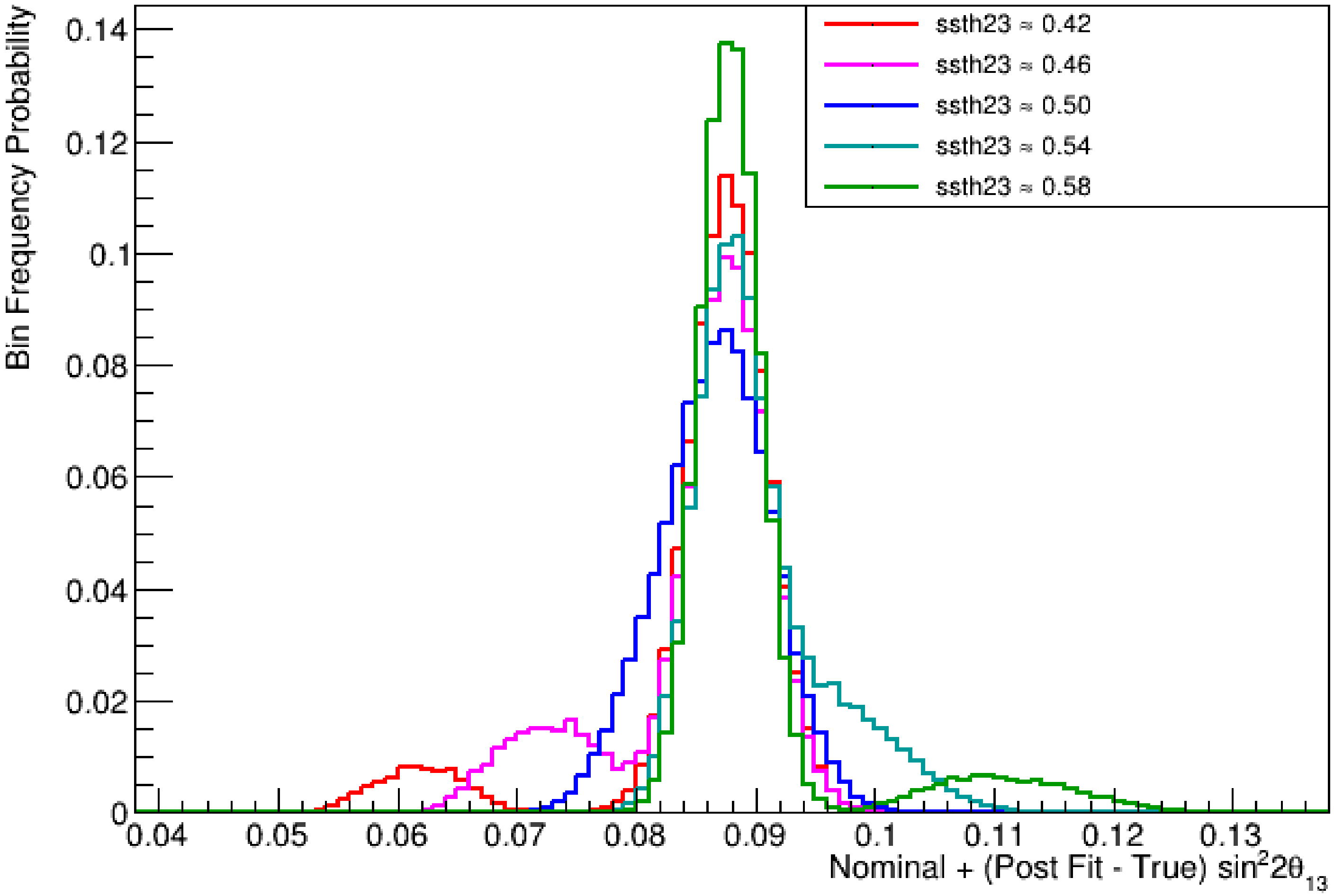


10 year exposure

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}

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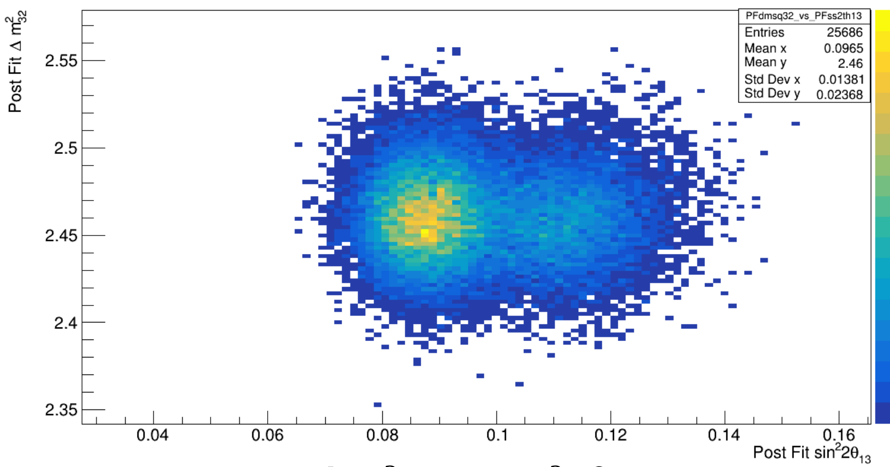
First single point analysis

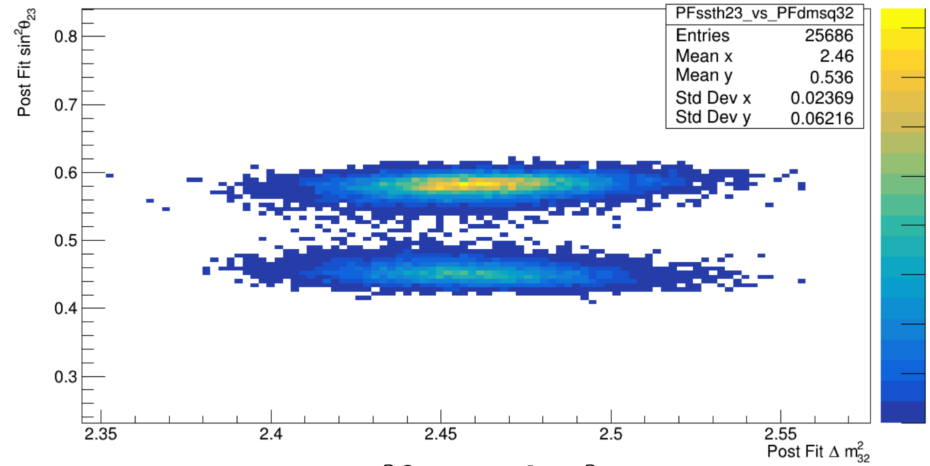
- Toy analysis fixed at single point in 4d true parameter space

Parameter	True Value
$\sin^2 2\theta_{13}$	0.088
Δm^2_{32}	2.45 X 10^{-3} eV
$\sin^2\theta_{23}$	0.58
δ_{cp}	-0.08π

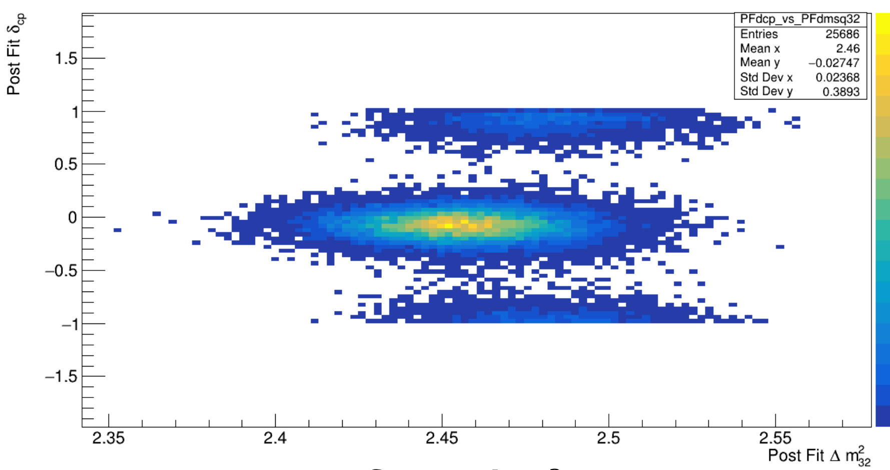
Parameters that appear weakly correlated or uncorrelated



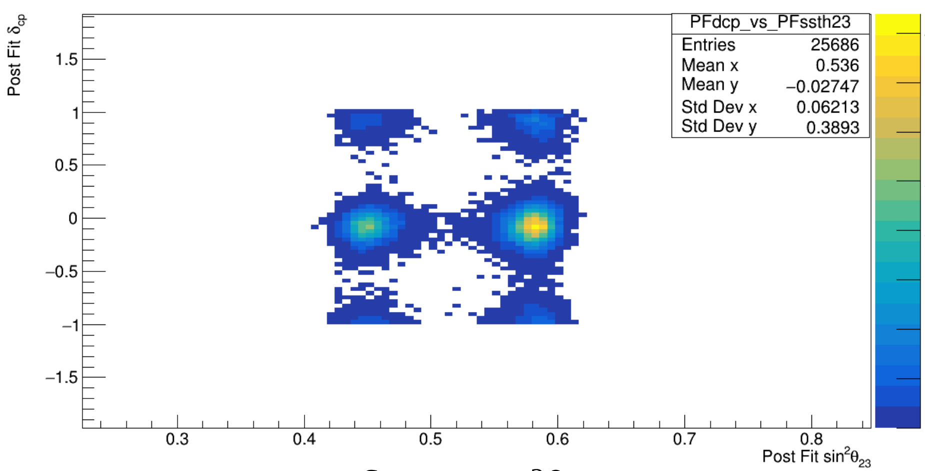
Δm^2_{32} vs $\sin^2 2\theta_{13}$



$\sin^2\theta_{23}$ vs Δm^2_{32}



δ_{cp} vs Δm^2_{32}



δ_{cp} vs $\sin^2\theta_{23}$

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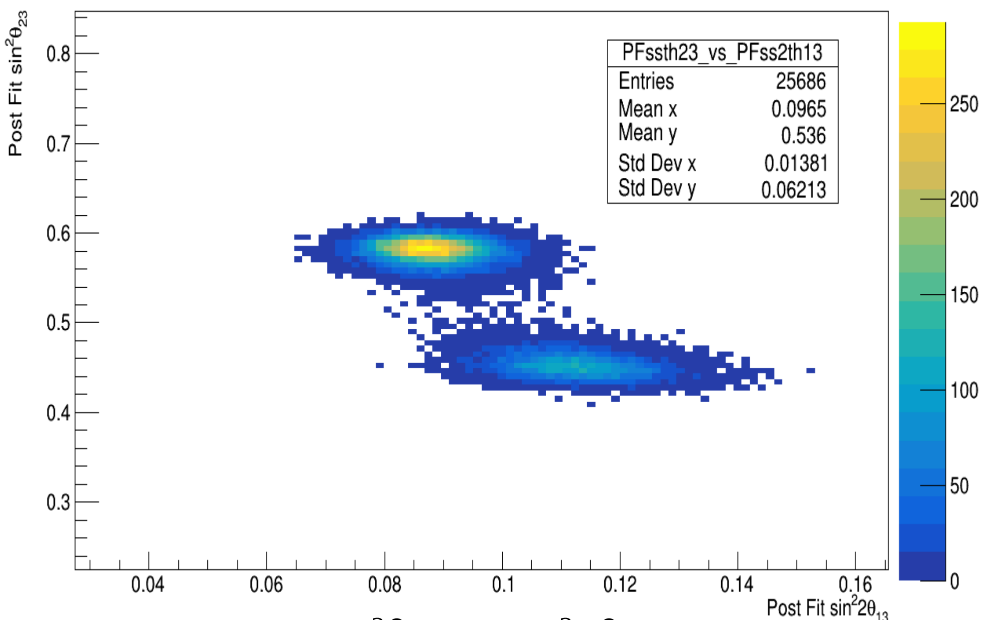
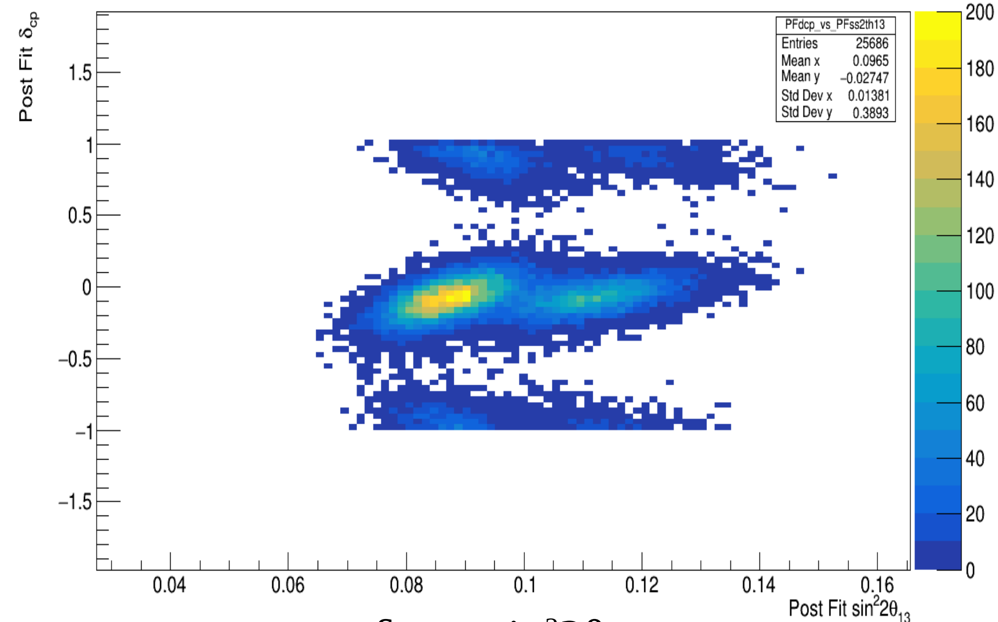
Candidate correlated parameters



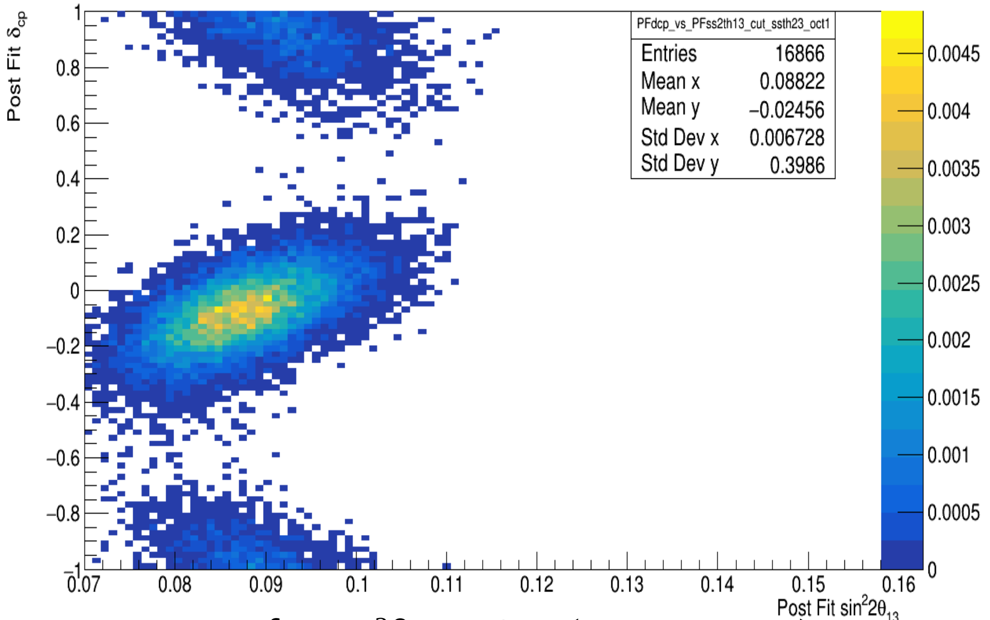
$\sin^2\theta_{23}$ vs $\sin^2 2\theta_{13}$



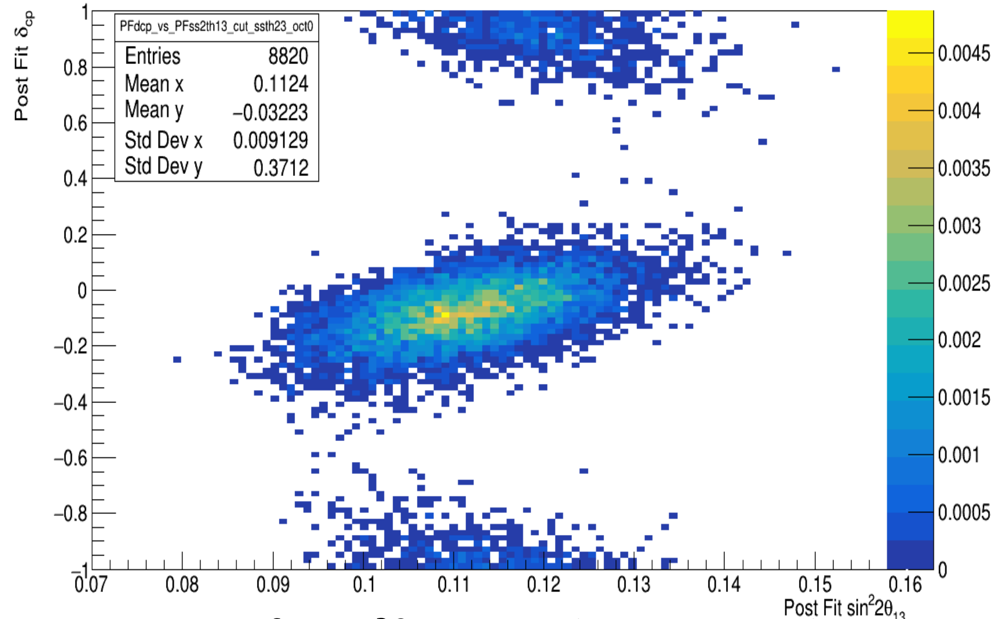
δ_{cp} vs $\sin^2 2\theta_{13}$

- Left: θ_{13}-θ_{23} octant error
- Right: Octant error visible in θ_{13}, correlation due to dominant ν_e appearance inverse proportionality to δ_{cp}

Fixed point δ_{cp} vs $\sin^2 2\theta_{13}$



Post fit $\sin^2\theta_{23} > 0.5$ (True octant)



Post fit $\sin^2\theta_{23} < 0.5$ (Error octant)

- Correlation strength weakly dependent on θ_{23} octant
  - Stronger in true octant
  - Allowed populations closer together in true octant

Next steps

- Investigate DUNE θ_{13} sensitivity to indirect test of PMNS non-unitarity when combined with Daya Bay θ_{13} constraint
- Pick interesting allowed points in true parameter space, run throws, explore correlations in 3d/4d post fit parameter space, determine how correlations affect 1σ, 90%, and 3σ confidence intervals
- Explore how increasing energy spectral information may resolve parameter degeneracies. Compare DUNE and HK resolution ability.