T2K Sensitivities at 25×10^{21} POT

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Motivation and Outline

Motivation:

- As the J-PARC beam power continues to increase, there may be the possibility to collect more T2K POT more quickly, or the possibility to request more beam time for T2K
  - This isn't an official T2K proposal, but instead part of a discussion about what would happen if the T2K run was extended
  - At higher statistics, reduction of systematic errors becomes even more important

Outline:

- T2K sensitivities with high statistics, analysis improvements
  - δ_{CP} sensitivities at higher POT
    - With different systematic error assumptions and horn currents
  - $\sin^2\theta_{23}$ and Δm^2_{32} sensitivities at 25×10^{21} POT
  - Sensitivity to MH by high-statistics T2K alone

Nominal Assumptions

The following were used in these studies unless otherwise stated:

- Joint fit of $\nu_e + \nu_\mu + \bar{\nu}_e + \bar{\nu}_\mu$
  - Fit to the Asimov (nominal) data-set – not the average of an ensemble of toy experiments
- True oscillation parameters: $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = -90°$, $\sin^2 \theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2, normal mass hierarchy
  - $\sim$ T2K, global best fit values
  - All four of these oscillation parameters are fit
- 5% error constraint on $\sin^2 2\theta_{13}$ from external (reactor) experiments (conservative "ultimate expected error")
- $\sim$2% systematic errors – see next slide
  - Fully correlated between ν- and $\bar{\nu}$-mode
- $\pm$250 kA horn current
- Assuming enhanced $\pi 0$ rejection using SK fiTQun $\pi 0$ cut
- See: Prog. Theor. Exp. Phys. (2015) 043C01 (T2K future sensitivity paper) for details about the fit procedure

Highlighted points are studied here

Systematic Error Implementation

- Systematic errors are implemented as in Prog. Theor. Exp. Phys. (2015) 043C01
  - Errors implemented as a covariance matrix binned in reconstructed neutrino energy
    - Bins for each of ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$
    - Fully correlated between ν and $\bar{\nu}$
    - Single nuisance parameter fit for each reconstructed energy bin
    - Matrix generated based on 2012 T2K oscillation analysis errors
  - So, errors on the reconstructed energy spectra shape are considered
- In the paper, assigned a $\sim$7% "conservative" future systematic error on the number of events at SK for both ν_e and ν_μ samples ($\sim$14% for $\bar{\nu}_e$ and $\bar{\nu}_\mu$)
  - 7%+14% reduced errors calculated by scaling 2012 error matrix
  - 2% systematic errors shown here:
    - Use the same error sizes for ν and $\bar{\nu}$ ($\sim$2%)
      $\rightarrow$ Scaled 7% errors down by a factor of 2/7 for 2% errors

$\rightarrow$ Obviously, reaching $\sim$2% systematic error level will take a lot of work by T2K analyzers

Statistics at 7.8×10^{21} and 25×10^{21} POT

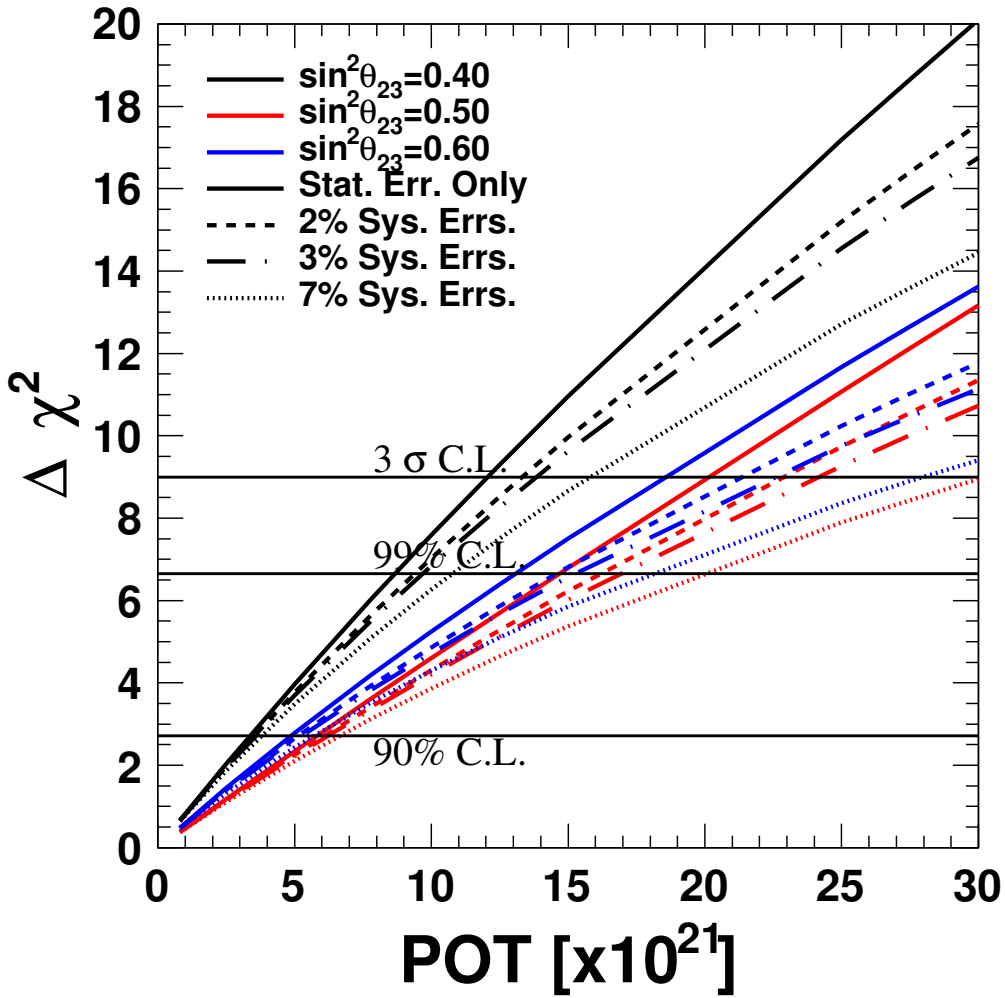
		ν_e signal	ν_e bkg.	$\bar{\nu}_e$ signal	$\bar{\nu}_e$ bkg.
7.8E21 POT	$\delta = 0$	98.2	26.8	25.6	16.3
	$\delta = -90°$	121.4	26.4	19.0	17.2
25E21 POT	$\delta = 0$	314	85.9	82.1	52.2
	$\delta = -90°$	389	84.6	60.9	55.1

* bkg includes wrong-sign

		ν_μ-mode	$\bar{\nu}_\mu$-mode
7.8E21 POT	w/o oscillation	2,648	1,007
	w/ oscillation	741	342
25E21 POT	w/o oscillation	8,519	3,228
	w/ oscillation	2,375	1,096

50% ν- + 50% $\bar{\nu}$-mode

Effect of Reduction of Systematic Errors

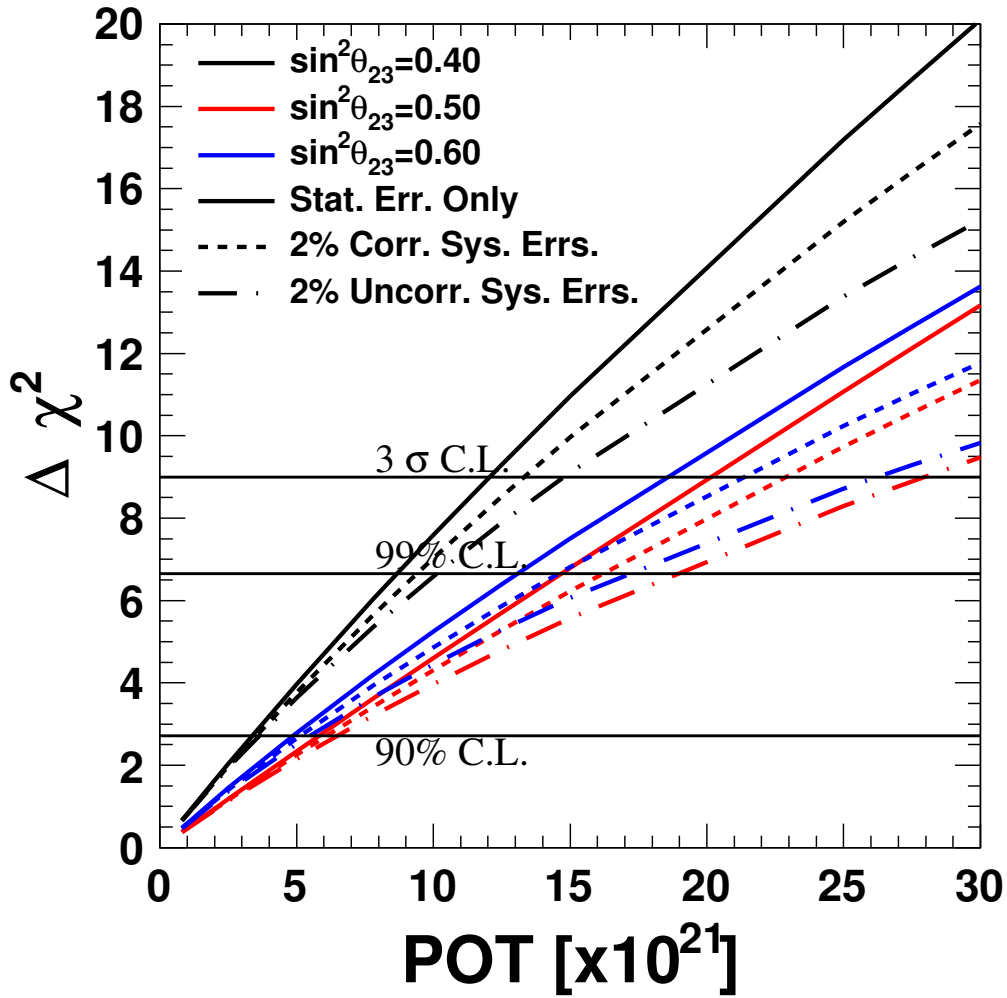


50% ν- + 50% $\bar{\nu}$-mode

True $\delta_{CP} = -90°$, true MH = NH

- $\Delta\chi^2$ for resolving non-zero δ_{CP} vs. POT
- Systematic error size matters!
  $\rightarrow$T2K measurement of δ_{CP} is systematics limited at high statistics
- Sensitivity depends on true value of $\sin^2\theta_{23}$ (and δ_{CP}, of course)
  - If errors can be reduced to 2%, T2K can make a $>3\sigma$ measurement of non-zero δ_{CP} for any value of $\sin^2\theta_{23}$ (at $\delta_{CP} = -90°$, NH)

Effect of Correlated vs. Uncorrelated Systematic Errors



50% ν- + 50% $\bar{\nu}$-mode

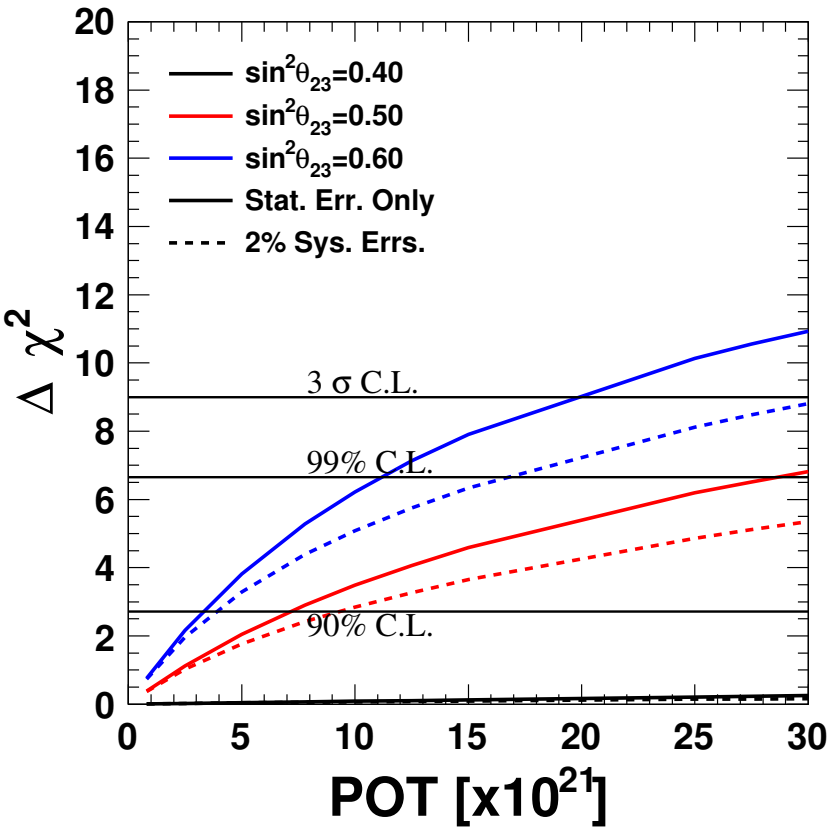
True $\delta_{CP} = -90°$, true MH = NH

- Errors are assumed either fully correlated or fully uncorrelated between ν- and $\bar{\nu}$-mode data
- Correlations between systematic errors matter! $\rightarrow$ Should try to keep systematics as correlated as possible for δ_{CP} measurement

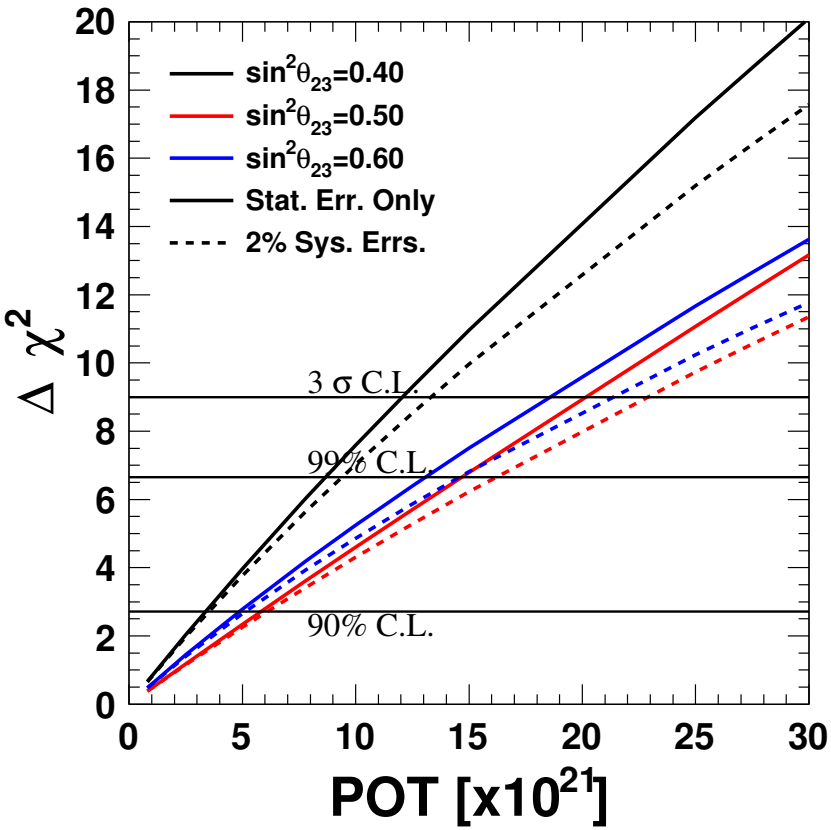
Importance of Taking ν- + $\bar{\nu}$-Mode Data

- T2K needs to take a combination of ν- + $\bar{\nu}$-mode to have highest sensitivity to a non-zero δ_{CP}

100% ν-mode



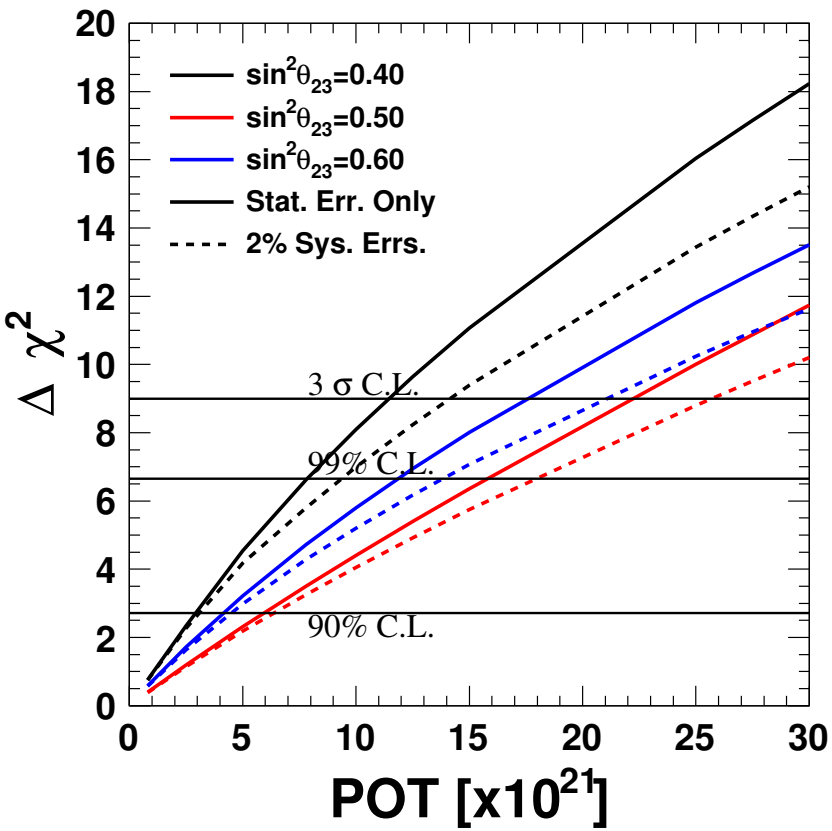
50% ν- + 50% $\bar{\nu}$-mode



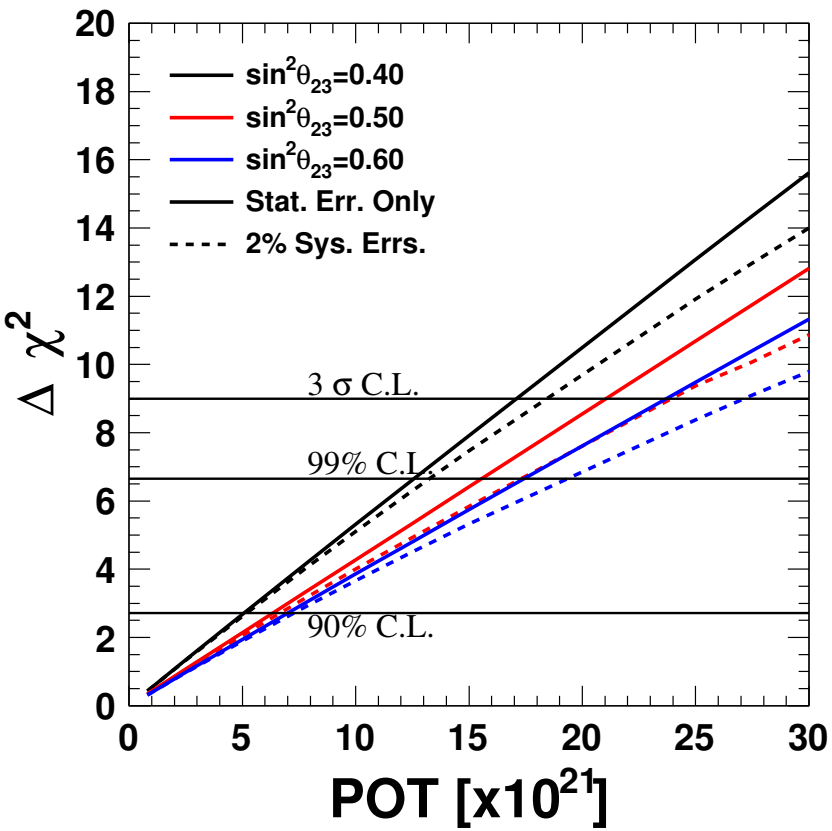
Different Ratios of ν- + $\bar{\nu}$-Mode Data

- Best choice of running ratio for maximum sensitivity to a non-zero δ_{CP} depends on the true value of $\sin^2\theta_{23}$
  - But ~50% ν- + 50% $\bar{\nu}$-mode gives best sensitivity for more possible values of $\sin^2\theta_{23}$ (including $\sin^2\theta_{23} = 0.5$)

67% ν- + 33% $\bar{\nu}$-mode



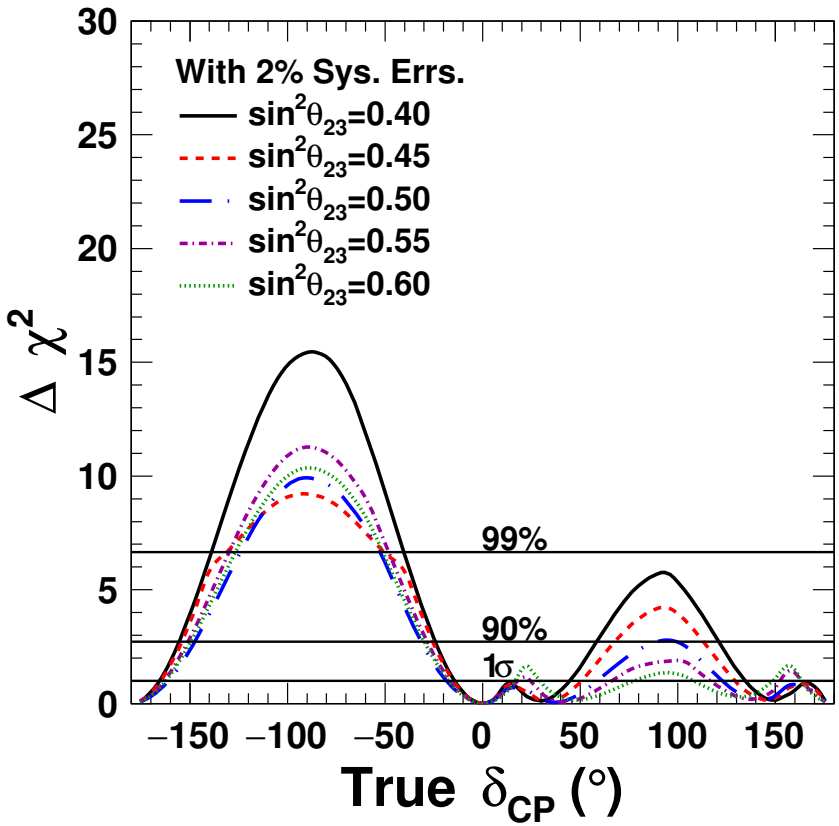
25% ν- + 75% $\bar{\nu}$-mode



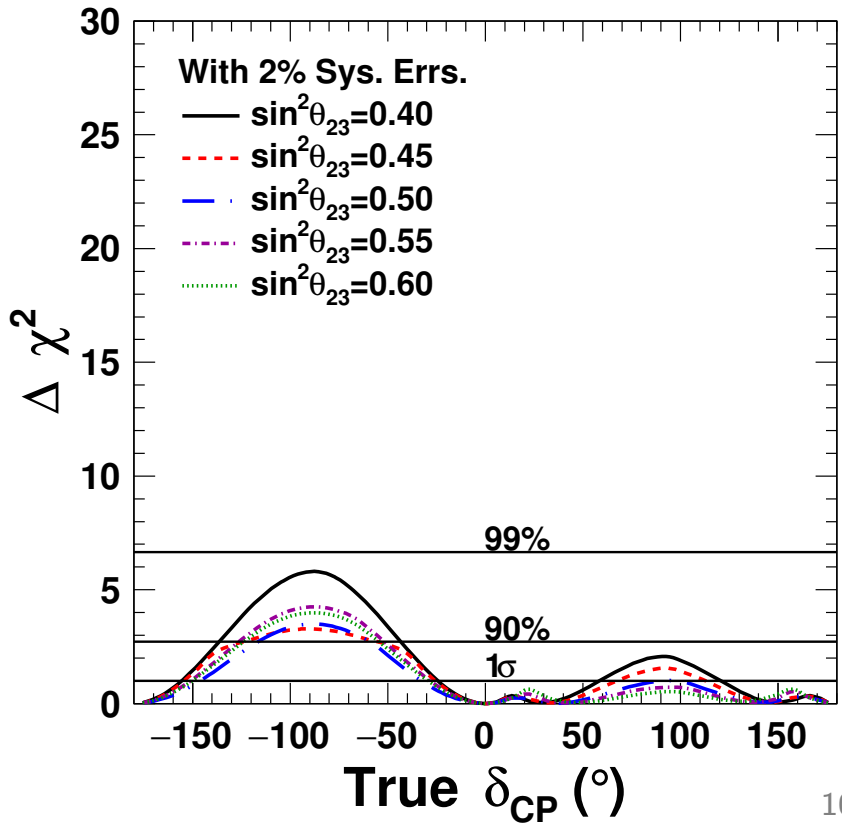
δ_{CP} Sensitivity vs. True δ_{CP}

- $\Delta\chi^2$ for resolving non-zero δ_{CP} vs. true δ_{CP}
- 50% ν- + 50% $\bar{\nu}$-mode
- Unknown MH (true NH)
- Sensitivity is best at $-90°$ (current best fit point)

25×10^{21} POT



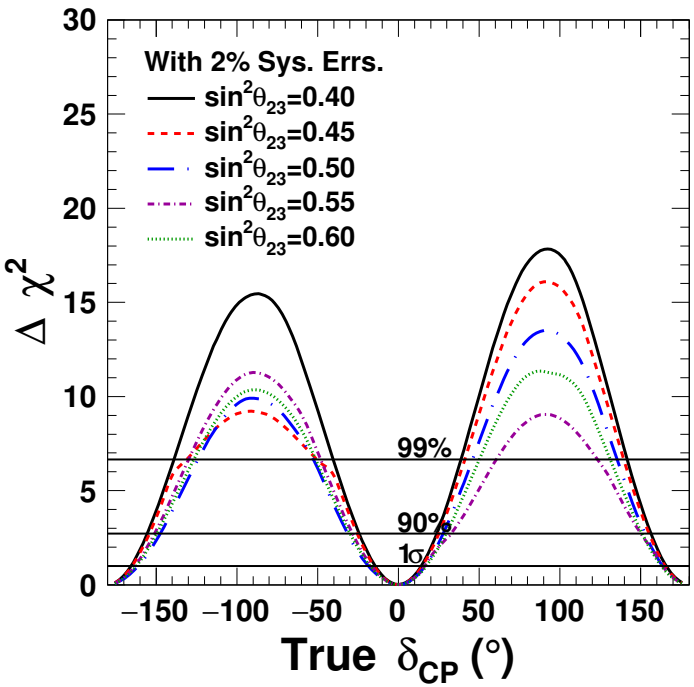
Full T2K Stats. (7.8×10^{21} POT)



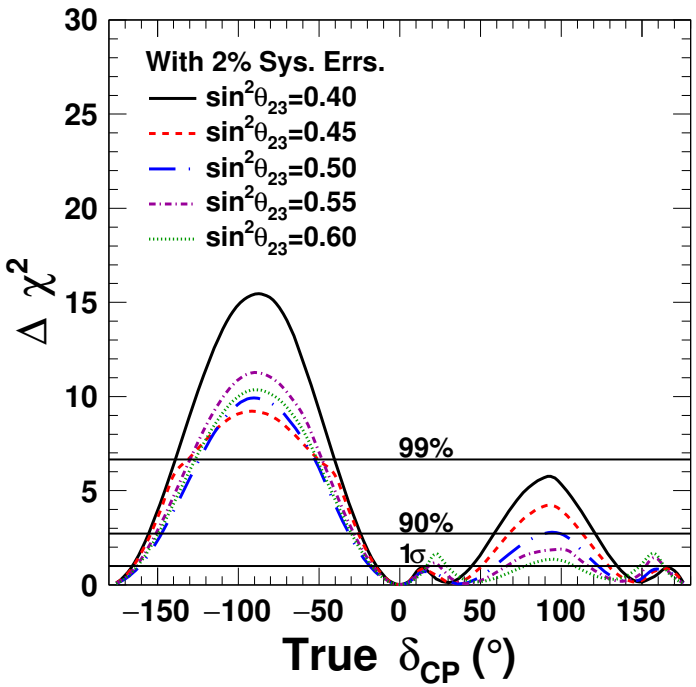
δ_{CP} Sensitivity vs. True δ_{CP}

- MH is known if an outside experiment measures the MH
- $\Delta\chi^2$ for resolving non-zero δ_{CP} vs. true δ_{CP}
- 50% ν- + 50% $\bar{\nu}$-mode, 25×10^{21} POT, true NH
- Sensitivity is greatly improved at $+90^\circ$ if MH is known
  - Known MH: $\Delta\chi^2$ is greater than 99% CL for 45% of δ_{CP} values, and greater than 3σ for 30% of δ_{CP} values
  - Unknown MH: $\Delta\chi^2$ is greater than 99% CL for 20% of δ_{CP} values, and greater than 3σ for 10% of δ_{CP} values

Known MH

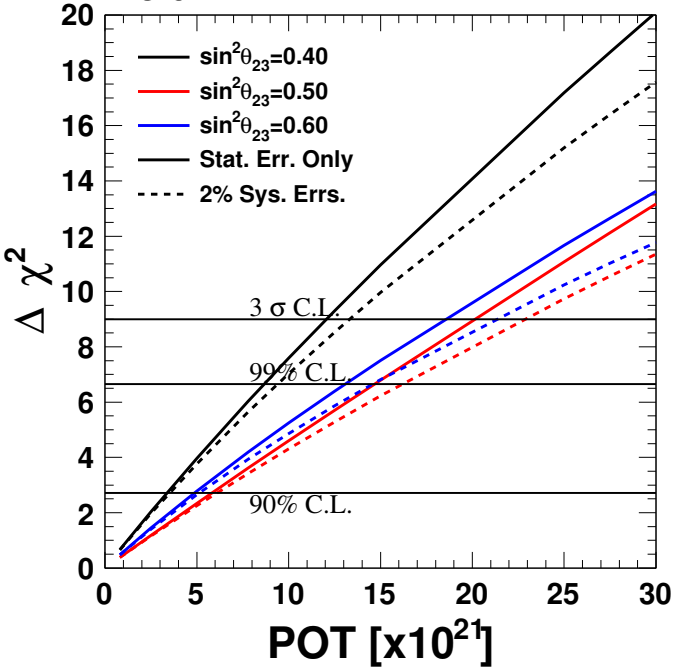


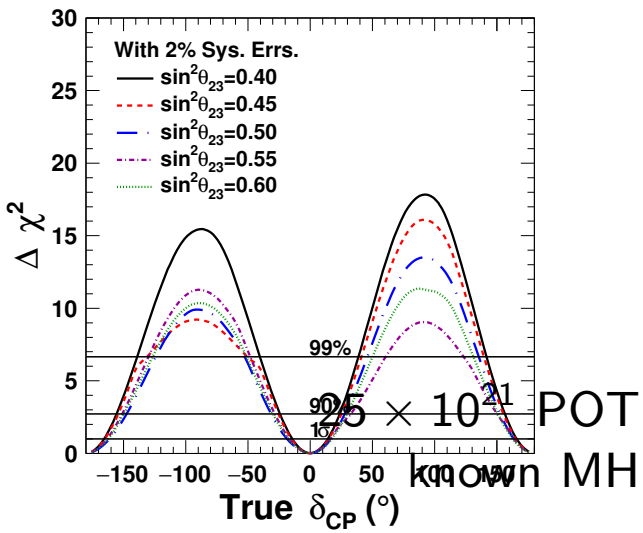
Unknown MH



Improvement at ±320 kA Horn Current

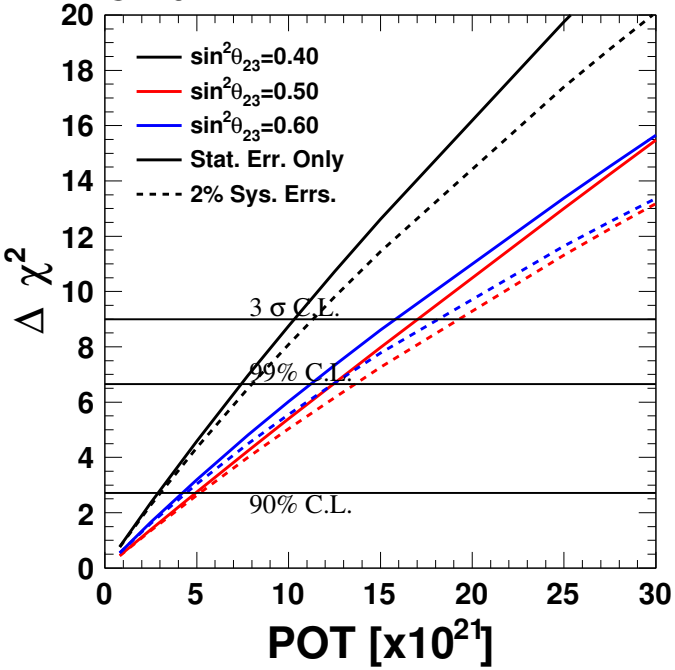
±250 kA Horn Current

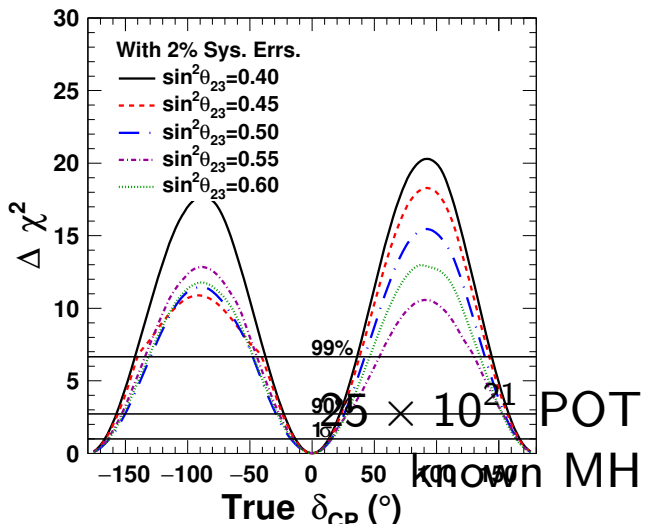




2.5×10^{21} POT known MH

±320 kA Horn Current





2.5×10^{21} POT known MH

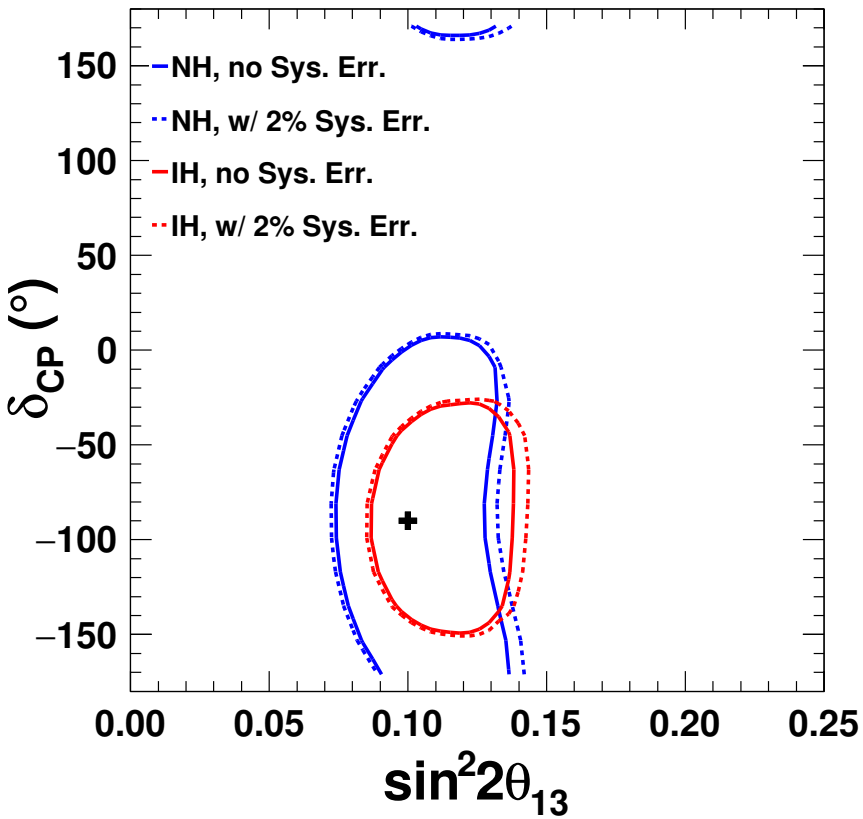
→

Enhanced signal, reduced background at ±320 kA

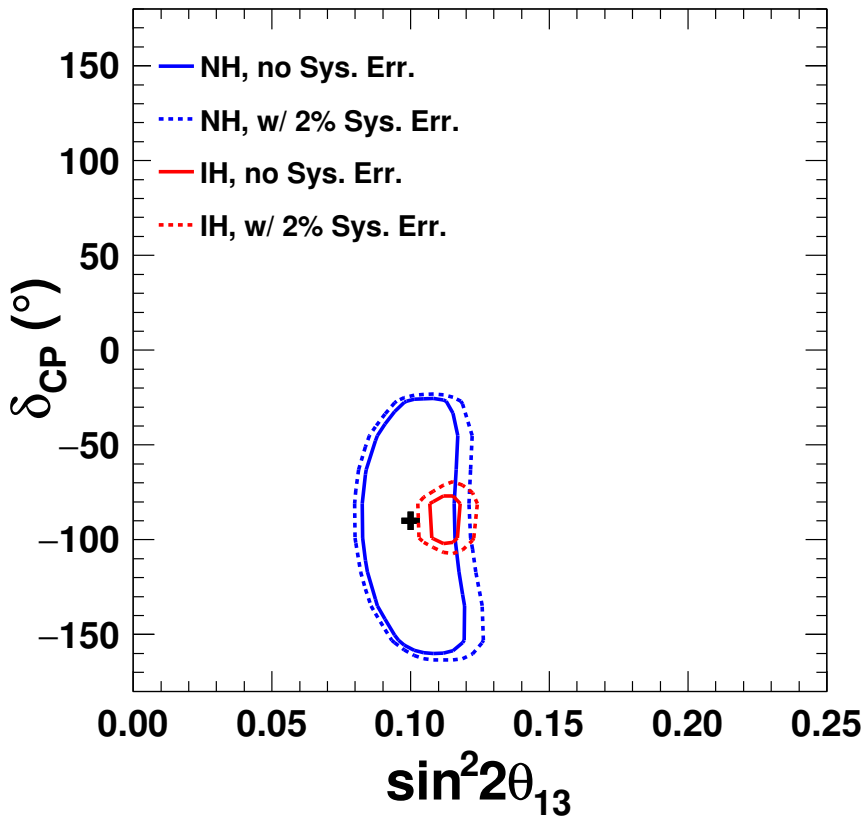
→ Substantial improvement

δ_{CP} vs. $\sin^2 2\theta_{13}$ Sensitivity 90% C.L. Contour

3.9×10^{21} POT ν- + 3.9×10^{21} POT $\bar{\nu}$-mode



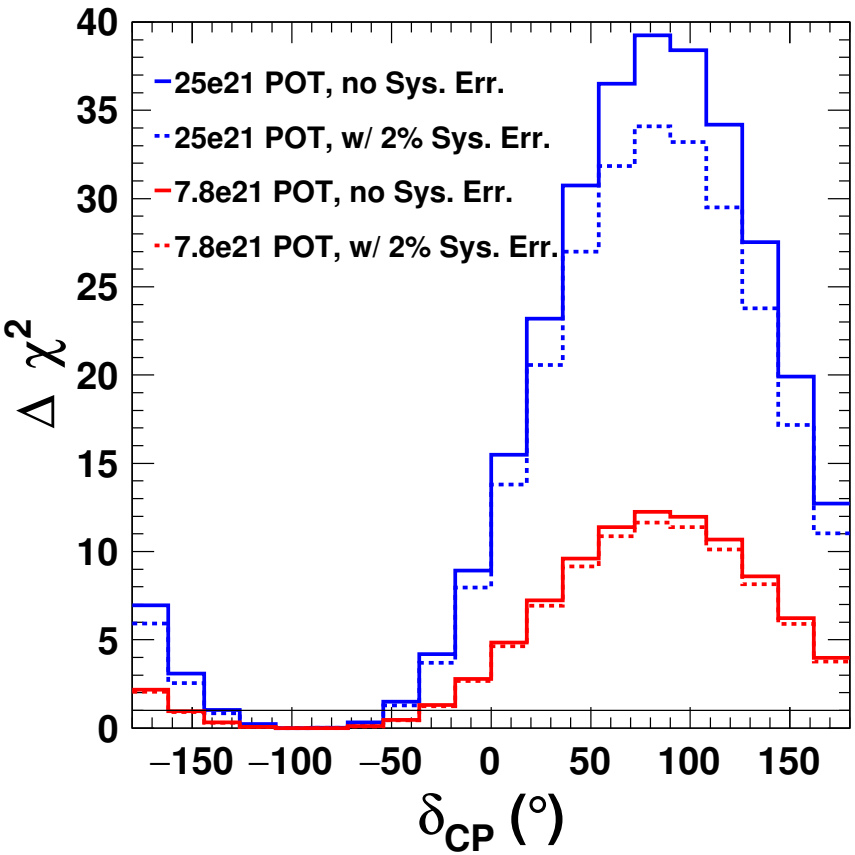
12.5×10^{21} POT ν- + 12.5×10^{21} POT $\bar{\nu}$-mode



No outside (reactor) constraint on $\sin^2 2\theta_{13}$

δ_{CP} Precision

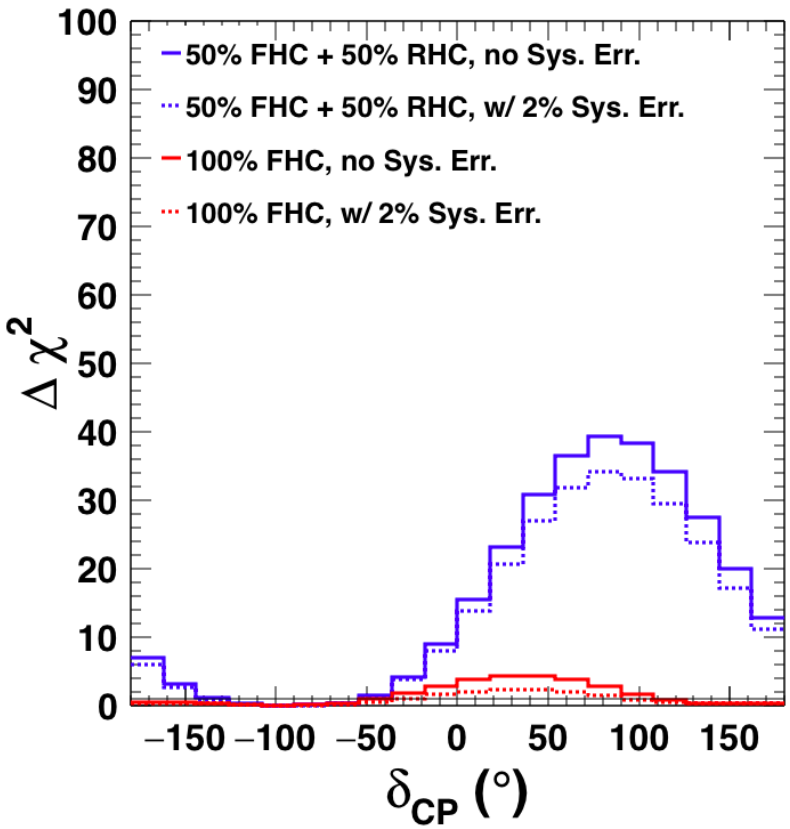
- NH (known), $\delta_{CP} = -90°$, $\sin^2\theta_{23} = 0.5$
- 25×10^{21} POT : σ ~36°(no sys. err.), ~45°(w/ 2% sys. err.)
- 7.8×10^{21} POT : σ ~63°
- Further improvement if constraint on $\sin^2 2\theta_{13}$ is used



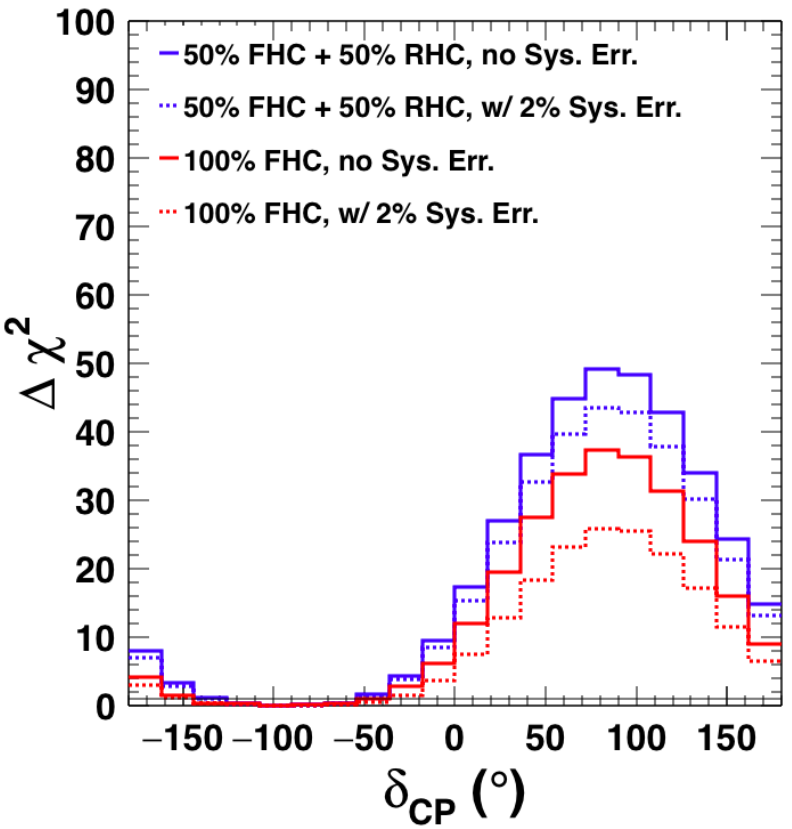
No outside (reactor) constraint on $\sin^2 2\theta_{13}$

δ_{CP} Sensitivity $\Delta\chi^2$ at 25×10^{21} Total POT

w/out Reactor

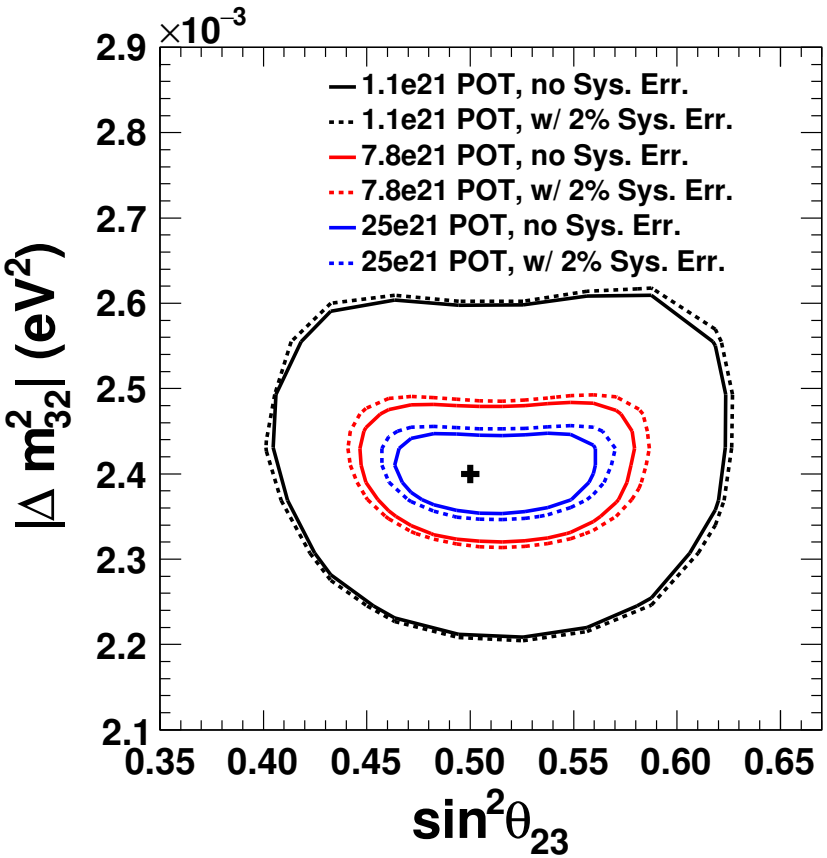


w/ Reactor

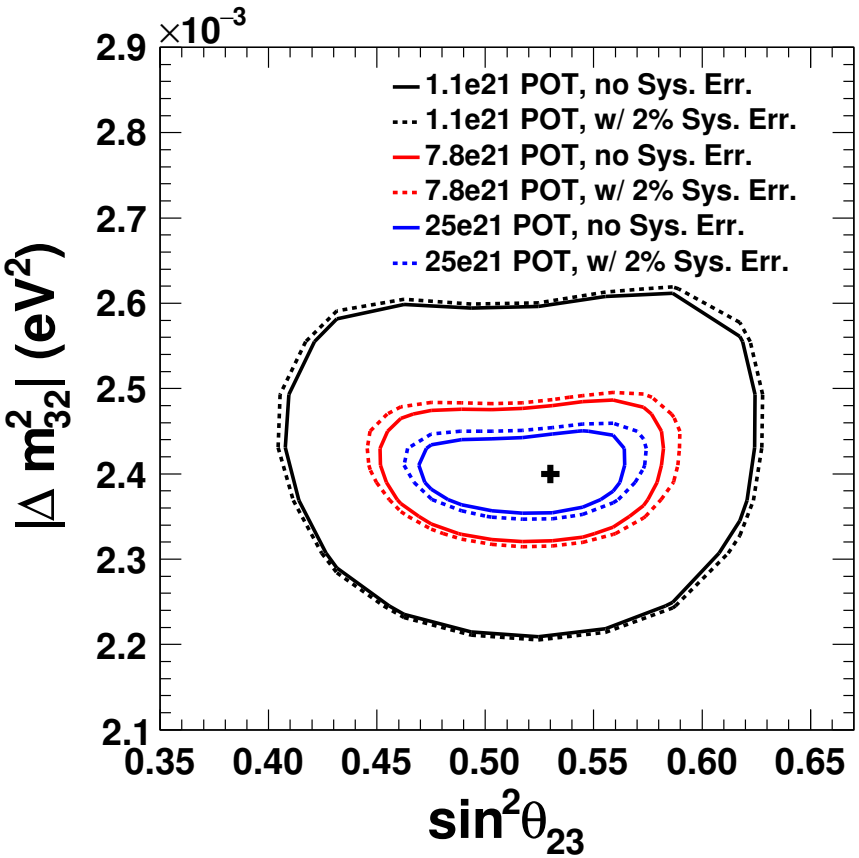


Δm^2_{32} vs. $\sin^2\theta_{23}$ Sensitivity 90% C.L. Contour

$\sin^2\theta_{23} = 0.5$



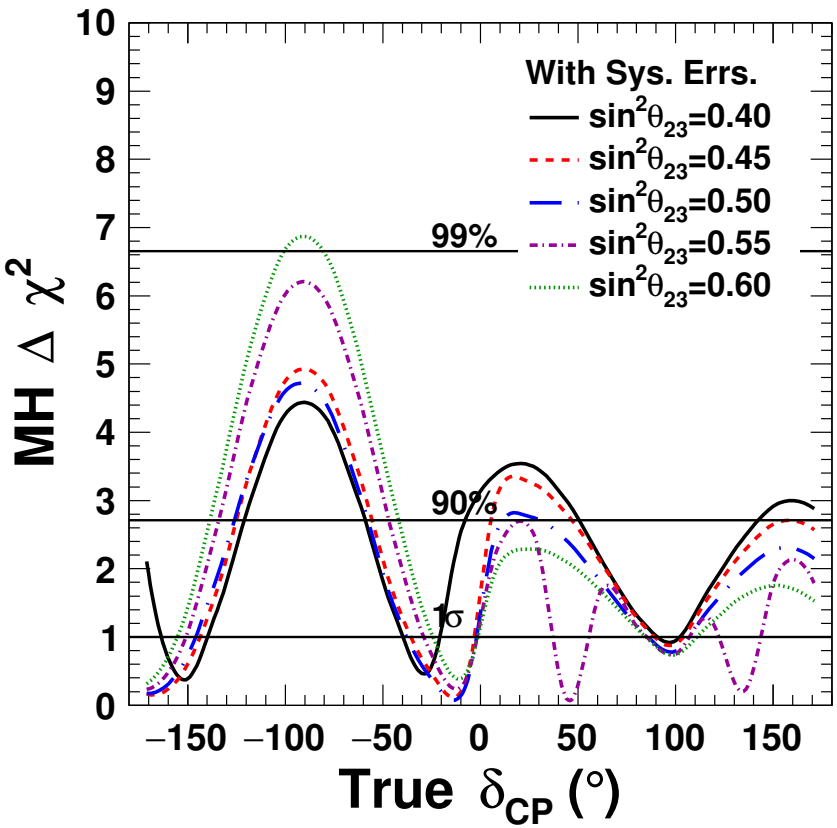
$\sin^2\theta_{23} = 0.53$



- Shown for NH only (true NH)
- Measurement at 25×10^{21} POT : $\theta_{23} = 45 \pm 1.9^\circ$
  - Current best measurement is $46 \pm 3^\circ$ by T2K

T2K Sensitivity to Resolving MH

- $\Delta\chi^2$ for resolving MH (true NH)
- 12.5×10^{21} POT ν- + 12.5×10^{21} POT $\bar{\nu}$-mode
- With 2% systematic errors
- Sensitivity isn't so great.. will be more significant when combined with NOνA results



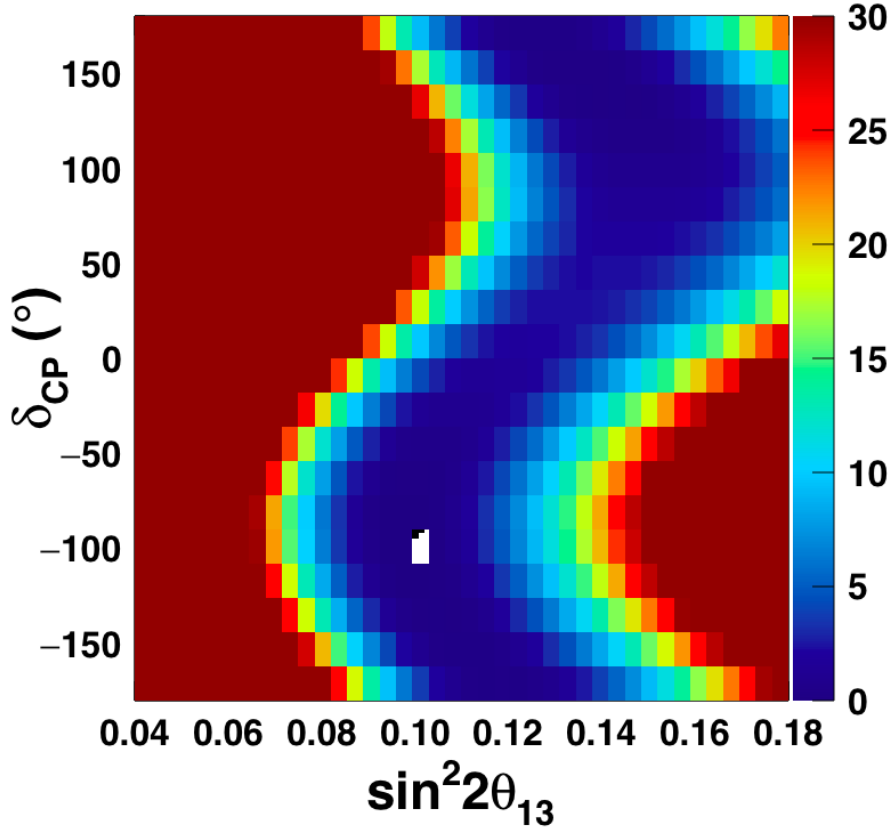
Conclusion

- At 25×10^{21} POT, 2% systematic errors, T2K can achieve $>3\sigma$ measurement of non-zero δ_{CP} (at true $\delta_{CP} = -90^{\circ}$, NH)
  - Reducing systematic errors as much as possible ($\rightarrow$ 2% systematic errors if possible) is beneficial
  - Increasing the horn current increases the sensitivity (or increases the speed at which T2K can reach high sensitivity)
- Possible T2K constraints on other parameters ($\sin^2\theta_{23}$, MH) are less impressive, but T2K can continue to help provide better constraints on these parameters, and can be a major contributor to global fits

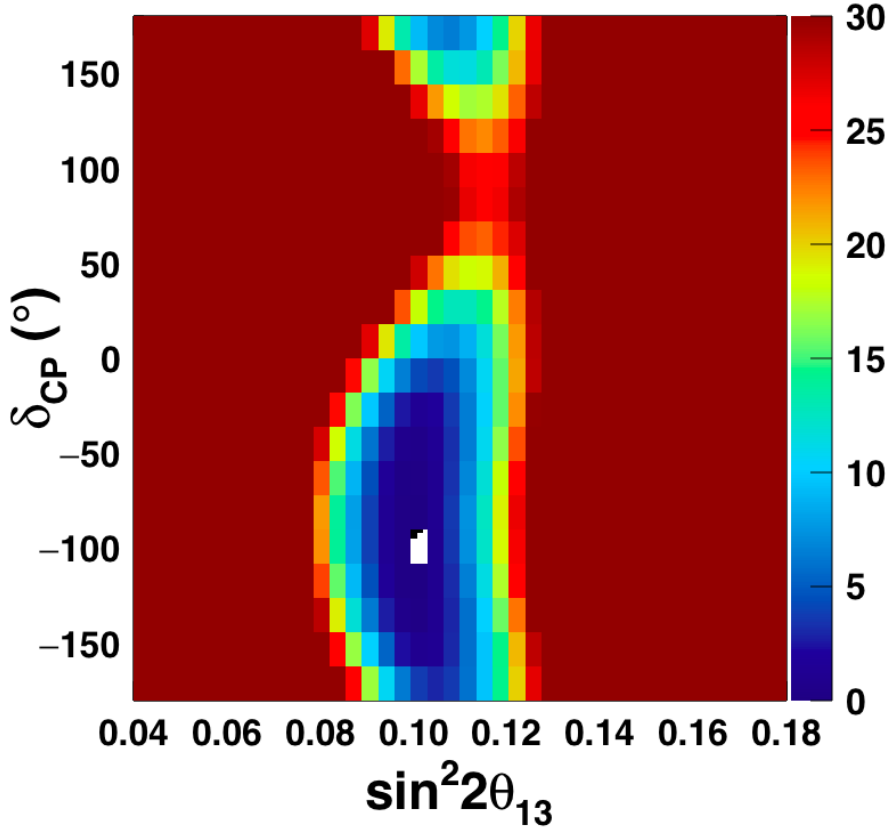
Backup Slides

δ_{CP} vs. $\sin^2 2\theta_{13}$ Sensitivity $\Delta\chi^2$: 25×10^{21} ν-Mode POT

w/out Reactor

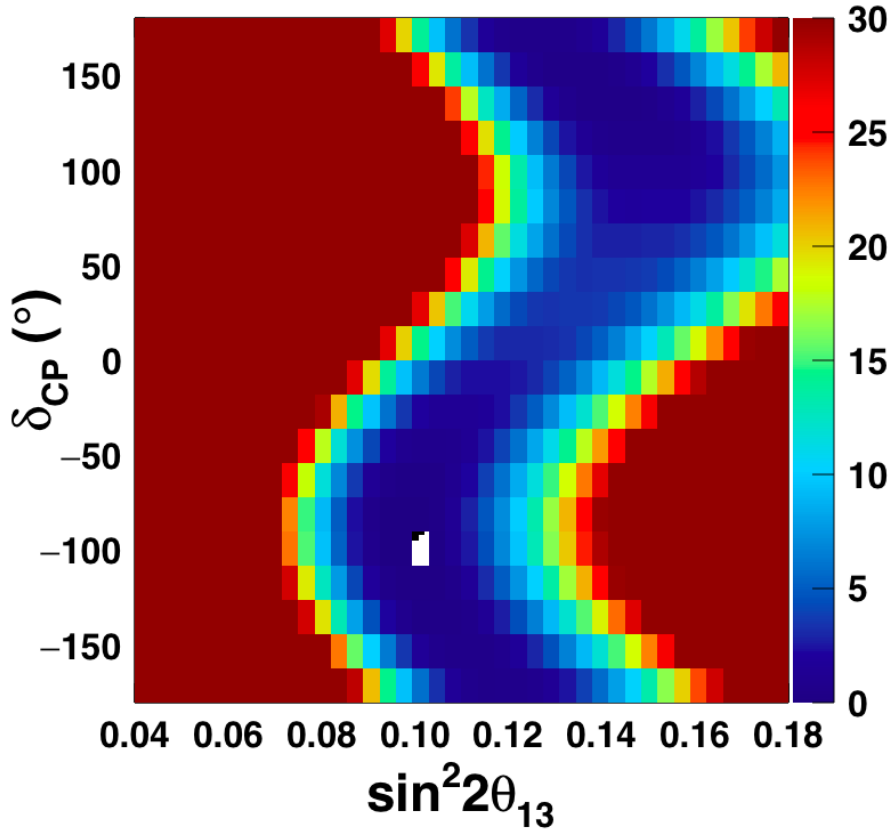


w/ Reactor



δ_{CP} vs. $\sin^2 2\theta_{13}$ Sensitivity $\Delta\chi^2$: 50×10^{21} ν-Mode POT

w/out Reactor



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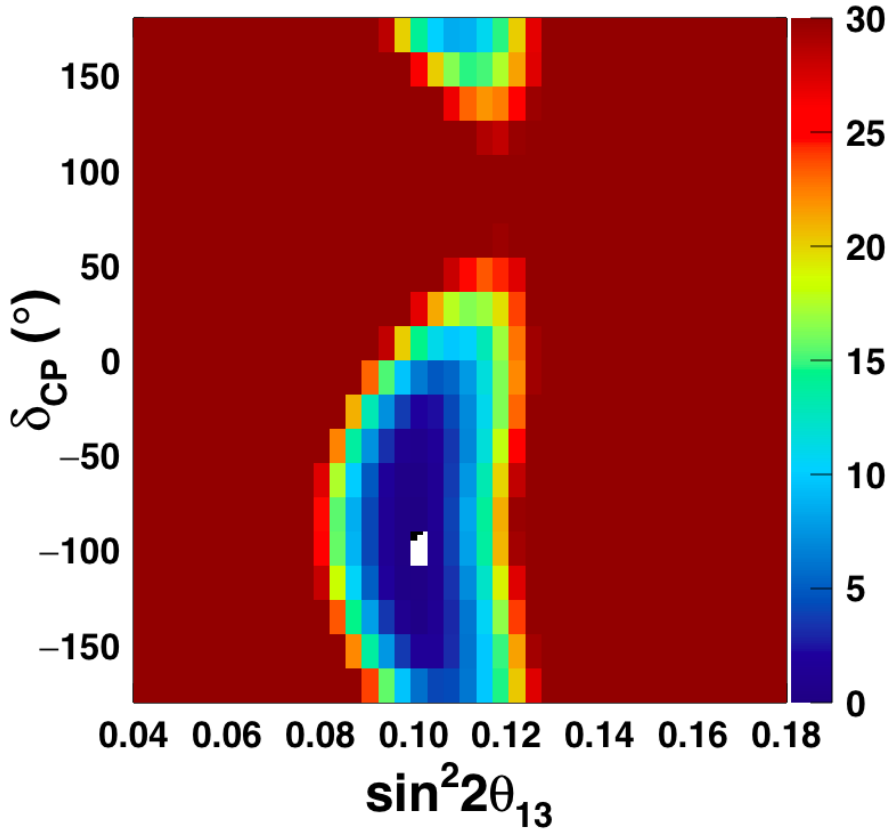

δ_{CP} vs. $\sin^2 2\theta_{13}$ Sensitivity $\Delta\chi^2$: 12.5×10^{21} ν- + 12.5×10^{21} $\bar{\nu}$-Mode POT

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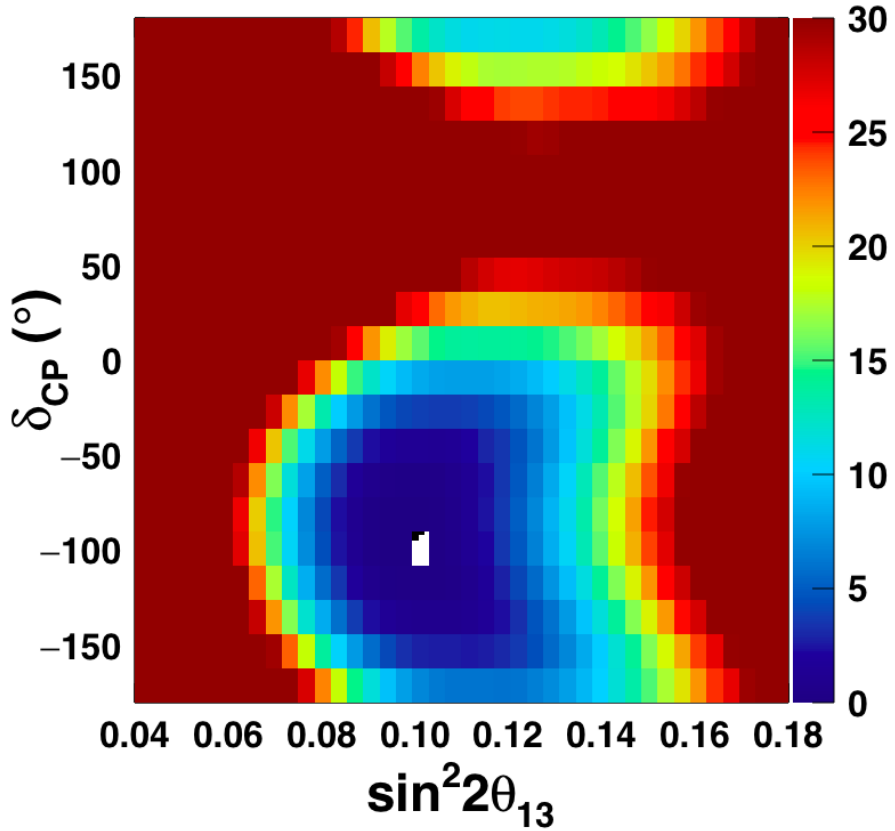

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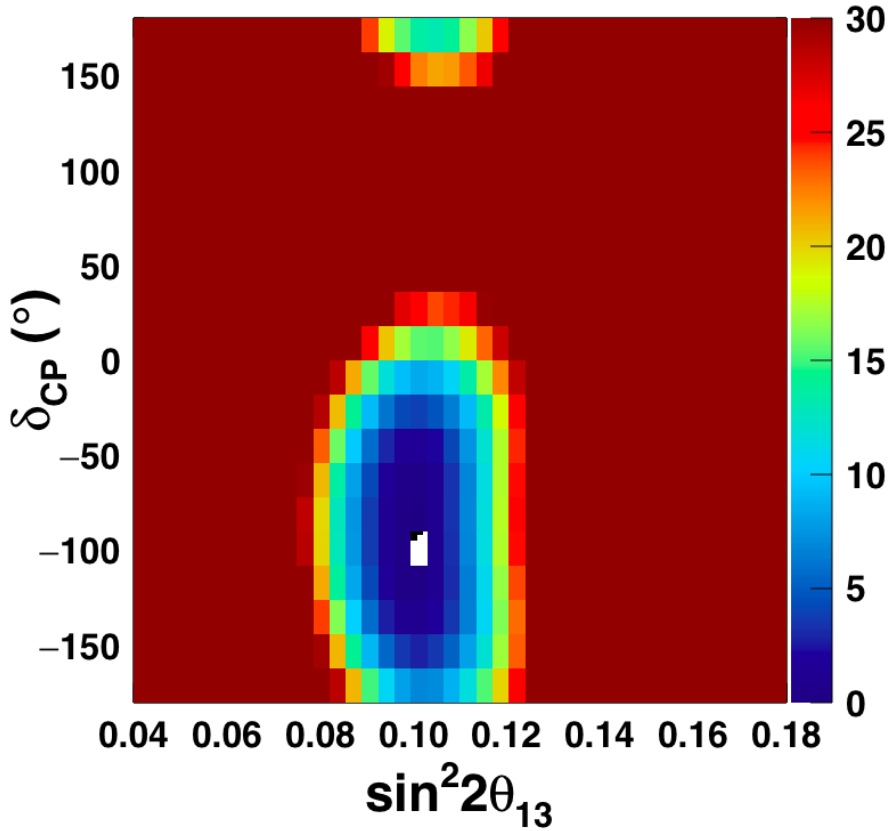

δ_{CP} vs. $\sin^2 2\theta_{13}$ Sensitivity $\Delta\chi^2$: 25×10^{21} ν- + 25×10^{21} $\bar{\nu}$-Mode POT

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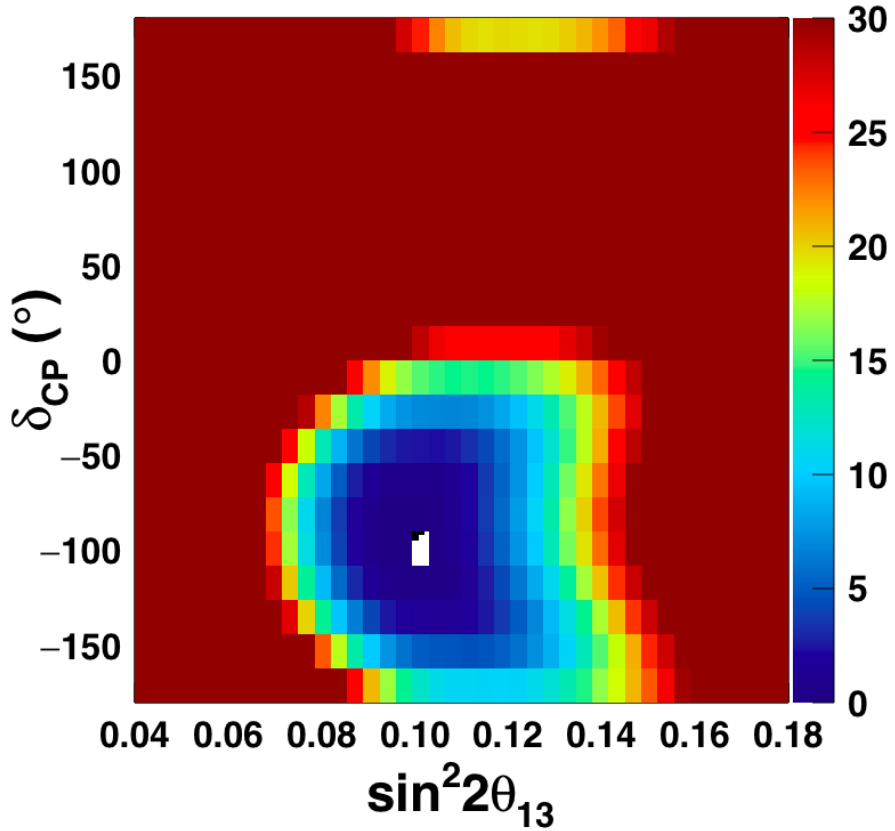

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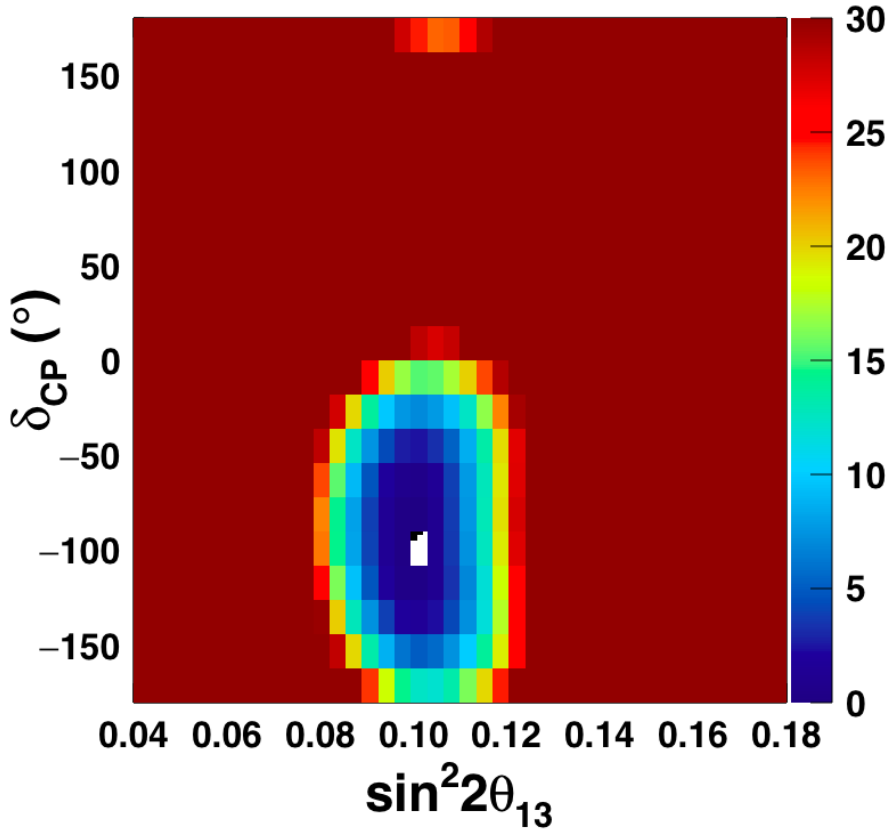
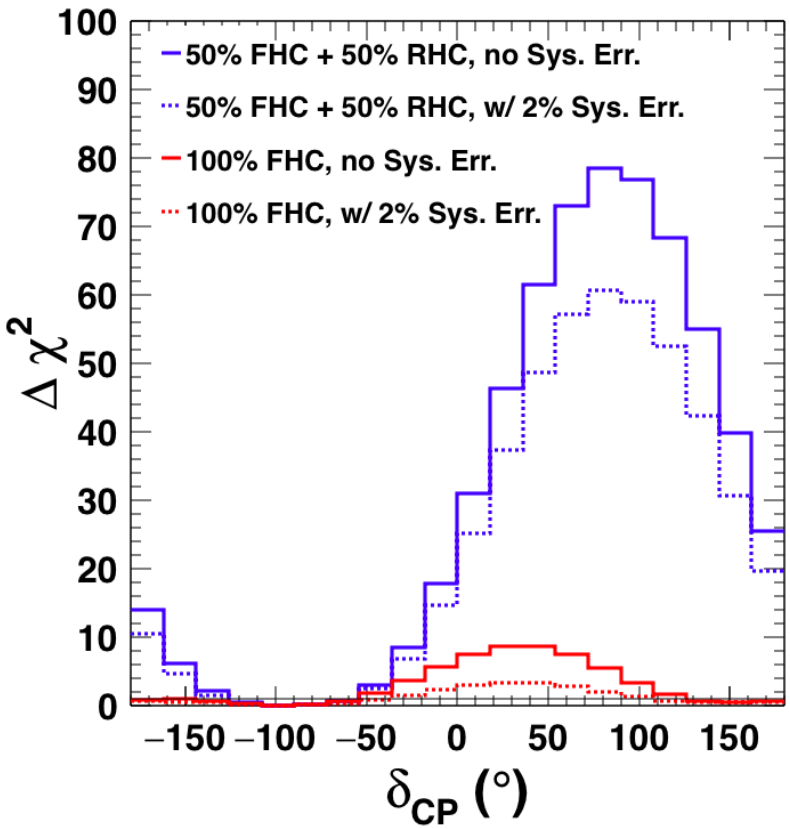


δ_{CP} Sensitivity $\Delta\chi^2$ at 50×10^{21} Total POT

w/out Reactor



w/ Reactor