VALOR sensitivity studies for HyperK

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Outline

- Quick introduction to the VALOR T2K 3-flavour oscillation fit
- Updates
- Confidence interval systematic uncertainty study
- Uncorrelated cross-section error study
- Summary

Introduction - VALOR 3-flavour analysis

- Joint measurement of: $sin^2\theta_{13}$, $sin^2\theta_{23}$, δ_{CP} and Δm^2_{23}
- Implements the agreed T2K 2013 analysis strategy.
- Analysis uses the *official* T2K 2013 inputs (MC and flux, cross-section and detector-response error assignments and correlations).
- Performs an indirect extrapolation by tuning the far detector Monte-Carlo to near detector constraints
- Neutrino oscillation probabilities calculated in a 3-active-neutrino framework, including matter effects in constant-density matter.
- Minimization: Binned likelihood ratio method, using MINUIT.

Introduction - Updates

Updates

- 10 years nominal annual exposure of 7.5 MW $\cdot$ 10^7 sec $= 1.56 \cdot 10^{22}$ POT
- Using $\pm$320kA horn current flux files (previously 250 kA)
- 1:3 FHC-RHC running ratio
- Consider 93 sources of systematic error (previously 65):
  1. 66 (33 + 33) Near detector correlated for FHC and RHC mode.
  2. 8 uncorrelated cross-section errors 100% correlated between FHC and RHC.
  3. 19 FSI + HK detector errors 100% correlated between FHC and RHC.

New studies

1. Studied the effect of improving the systematic uncertainties on the sensitivity to measure δ_{cp}, $sin^2(\theta_{13})$, $sin^2(\theta_{23})$ and Δm^2_{23}. Looking at the difference in 2D confidence intervals for different configurations of systematic uncertainty.
2. Dominant uncorrelated cross-section systematics by their effect on oscillation parameter fits. Looking at the effect when individually tweaking the systematic errors.

List of systematics considered

Type	Systematics	Comment	N_{syst}	N_{tot}
ND correlated (FHC)	f_0^{banff} - f_{24}^{banff}	ν_μ flux	11	
		$\bar{\nu}_\mu$ flux	5	
		ν_e flux	7	
		$\bar{\nu}_e$ flux	2	
	f_{25}^{banff}	CCQE axial mass	1	
	f_{26}^{banff}	Resonant axial mass	1	
	f_{27}^{banff}-f_{28}^{banff}	CCQE Norm	3	
	f_{30}^{banff}-f_{31}^{banff}	CC1π Norm	2	
	f_{32}^{banff}	NC1π^0	1	33
ND correlated (RHC)	FHC * 1.06			33
Uncorrelated	f_{WShape}	π p-distribution (50%)	1	
	$f_{\pi-less\Delta}$	πless Δ decay (5%)	1	
	f_{CCcoh}	σ CC coherent (50%)	1	
	f_{NCoth}	σ NC other (30%)	1	
	f_{NCcoh}	σ NC coherent (30%)	1	
	$f_{NC\pi}$	σ NCπ (30%)	1	
	$f_{CC\nu_e/\nu_\mu}$	$\sigma_{\nu_e}/\sigma_{\nu_\mu}$ (3%)	1	
	$f_{CC\bar{\nu}/\nu}$	$\sigma_{\bar{\nu}}/\sigma_\nu$ (6%)	1	8
SK/$\sqrt{20}$ + FSI	f_E	Energy scale	1	
	$f_0^{SK} - f_5^{SK}$	$1R_\mu$ efficiencies	6	
	$f_6^{SK} - f_{17}^{SK}$	$1R_e$ efficiencies	12	19
				93

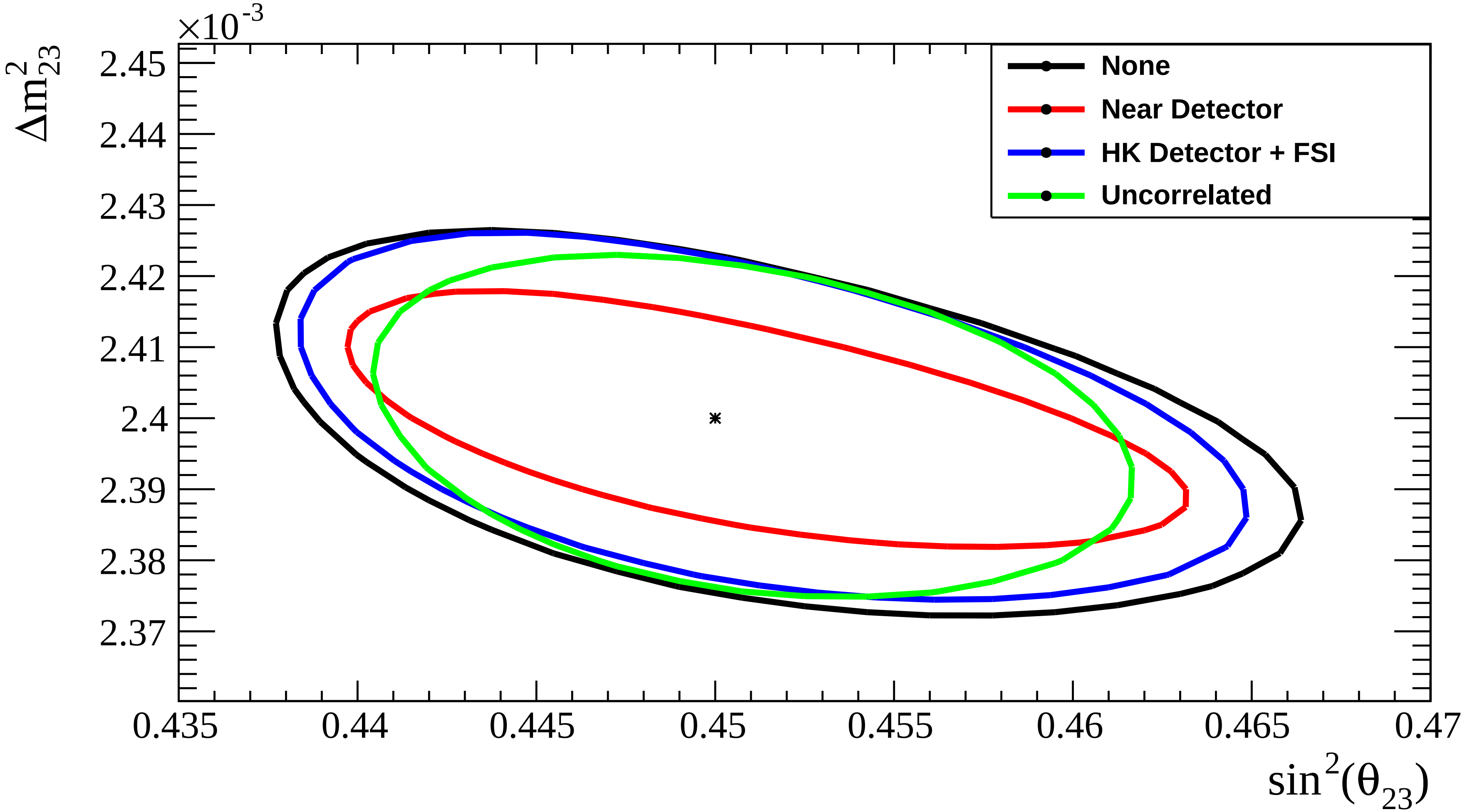
Calculation of oscillation sensitivity

Study was performed in the following way:

- Generate toy MC spectra with nominal systematic parameters and oscillation parameters given below. Without statistical fluctuations.
- Find min χ^2 at each point on a 2D grid with the 2 oscillation parameters fixed. All others fit.
- Compare cases where a group of systematic parameters are fixed to the value the toy MC spectra were generated with (fully constrained).
    - None (All sources of systematic error)
    - Near detector correlated (BANFF)
    - FSI and HK detector
    - Uncorrelated cross-section

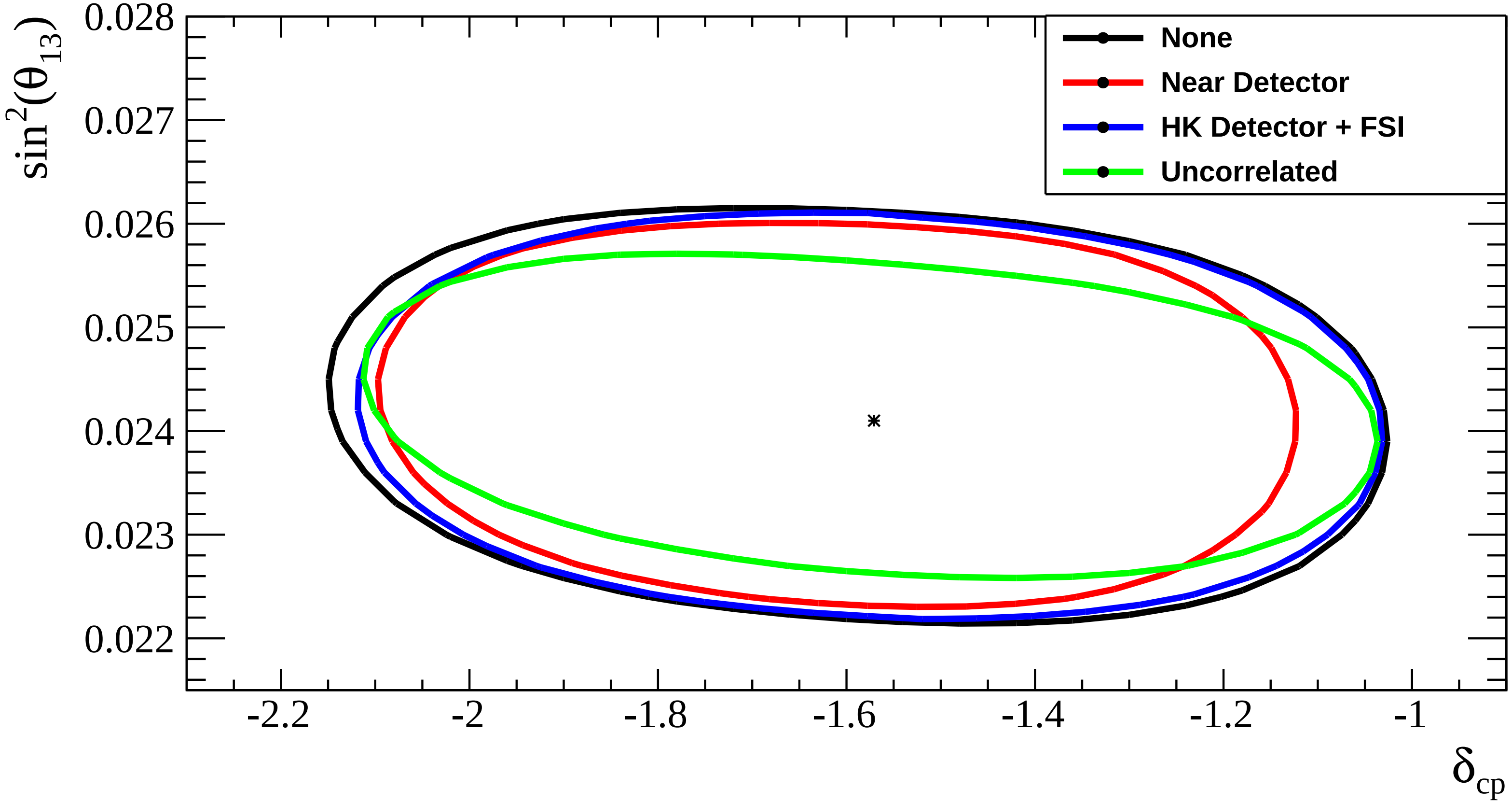
$sin^2(\theta_{13}) = 0.0241$, $sin^2(\theta_{23}) = 0.45$, $sin^2(\theta_{12}) = 0.306$, $\Delta m^2_{12} = 7.5 \cdot 10^{-5} eV^2$, $\Delta m^2_{23} = 2.4 \cdot 10^{-3} eV^2$, $\delta_{cp} = -\frac{\pi}{2}$, normal hierarchy

$sin^2(\theta_{23})$-Δm^2_{23} Sensitivity (90% Confidence)



- Biggest reduction comes from constraining near detector correlated and uncorrelated cross-section errors

$sin^2(\theta_{13})$-δ_{cp} Sensitivity (90% Confidence)



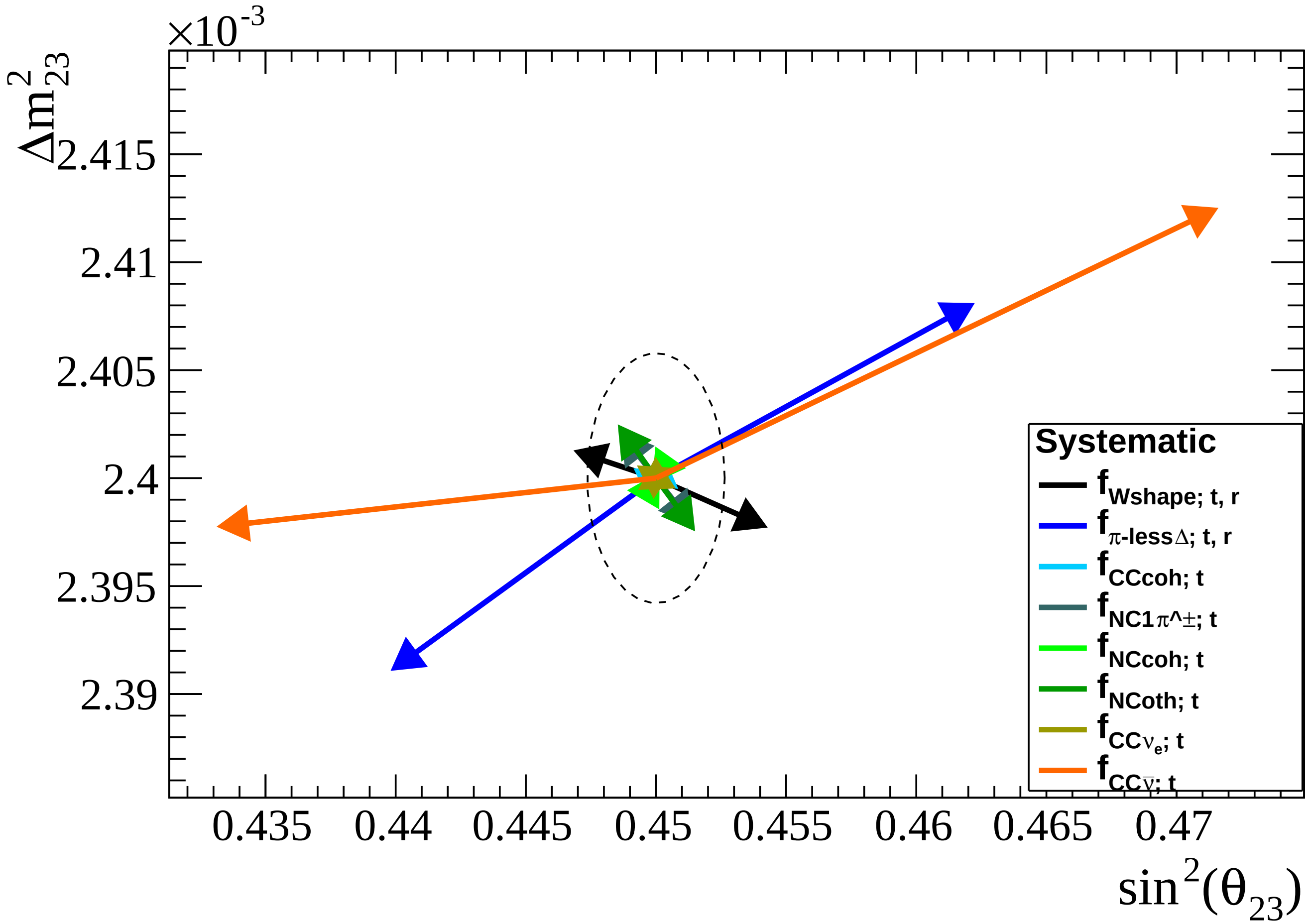
- With reactor constraint
- Biggest again from uncorrelated cross section errors ($sin^2(\theta_{13})$) and near detector correlated errors (δ_{cp})

The Impact of uncorrelated cross-section errors

Study was performed to determine which errors cause the best fit points of oscillation parameters to vary the most. Uncorrelated are the ones that the near detector can not provide constraints for.

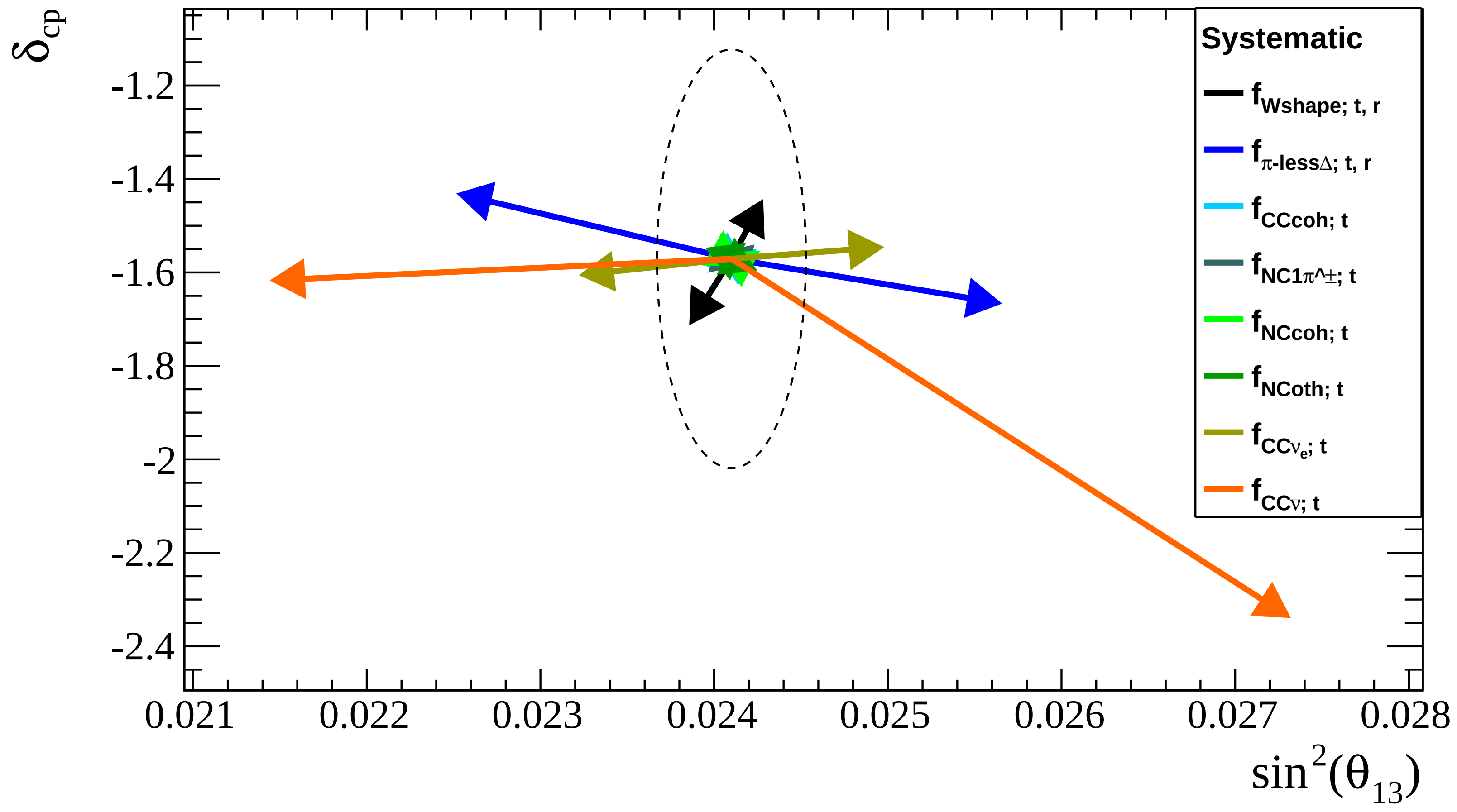
1. Generate toy MC spectra for each systematic ($\pm\sigma$) without statistical fluctuations
2. Perform fits for only the oscillation parameters (all systematics fixed to nominal)
3. Plot shows best fit points of fits and distance from nominal oscillation parameters
4. Effect of statistical fluctuations found by generating 1000 toys and taking the standard deviation of each oscillation parameter.
5. Standard deviations were then used to draw the ellipse which is a measure of the statistical uncertainty.

Impact on $sin^2(\theta_{23})$ and Δm^2_{23}



$\frac{\sigma_{\bar{\nu}}}{\sigma_{\nu}}$, π-less Δ decay and initial π momentum distribution have largest effect.

Impact on $sin^2(\theta_{13})$ and δ_{cp}



$\frac{\sigma_{\bar{\nu}}}{\sigma_{\nu}}$, π-less Δ decay and $\frac{\sigma_{\nu_e}}{\sigma_{\nu_\mu}}$ have the largest effect.

Summary

90% Contour study

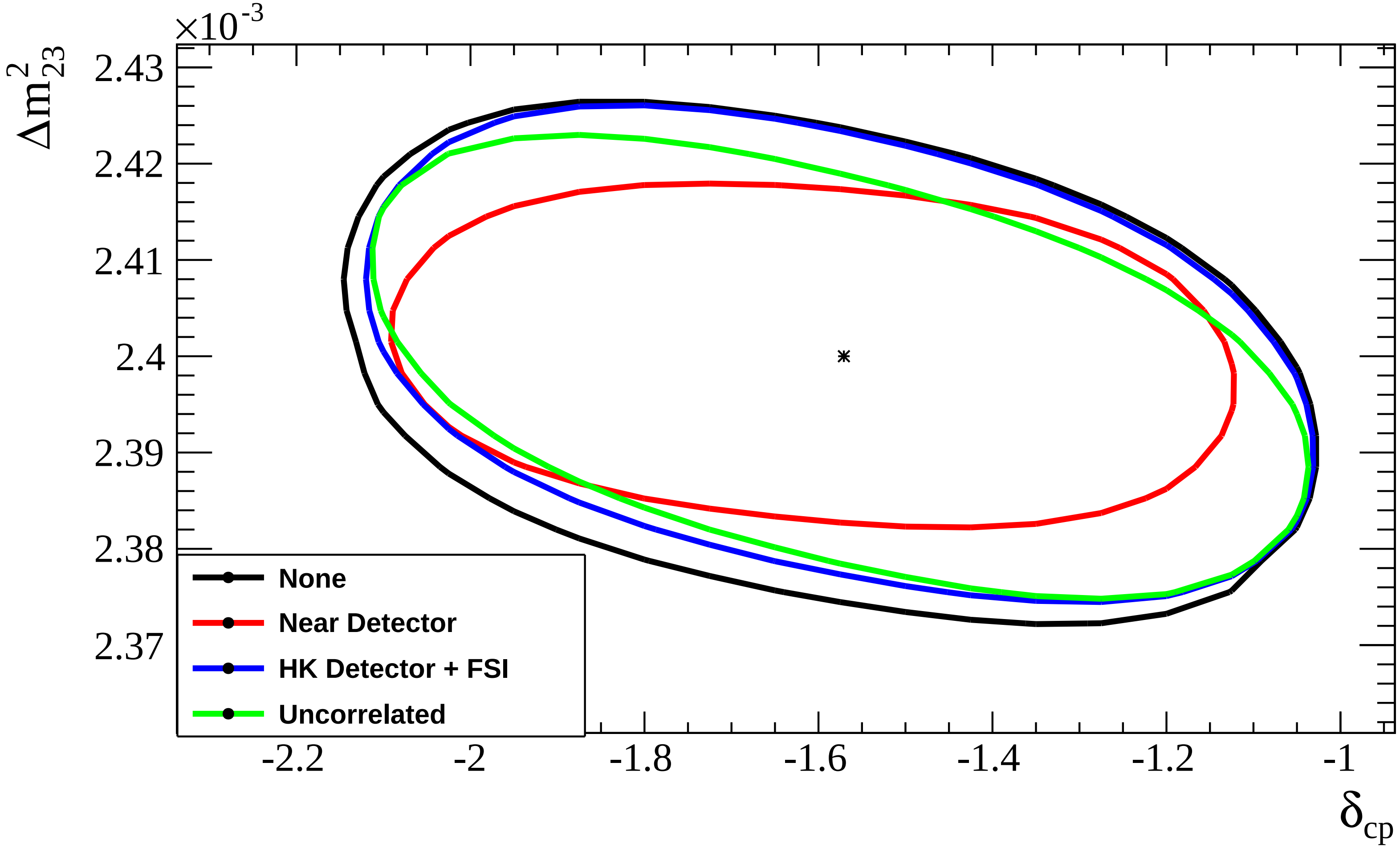
- Found that further constraining the HK detector and FSI systematics cause the smallest reduction in confidence interval.
- Constraining the near detector correlated parameters and the uncorrelated cross-section parameters will give similar reduction but in different directions.

Uncorrelated cross-section study

- Found 4 out of the 8 uncorrelated cross section systematics cause a $> 1\sigma$ shift in the best fit point. Most significant is the $\frac{\sigma_{\bar{\nu}}}{\sigma_{\nu}}$ error.

backups

90% intervals for Δm^2_{23}



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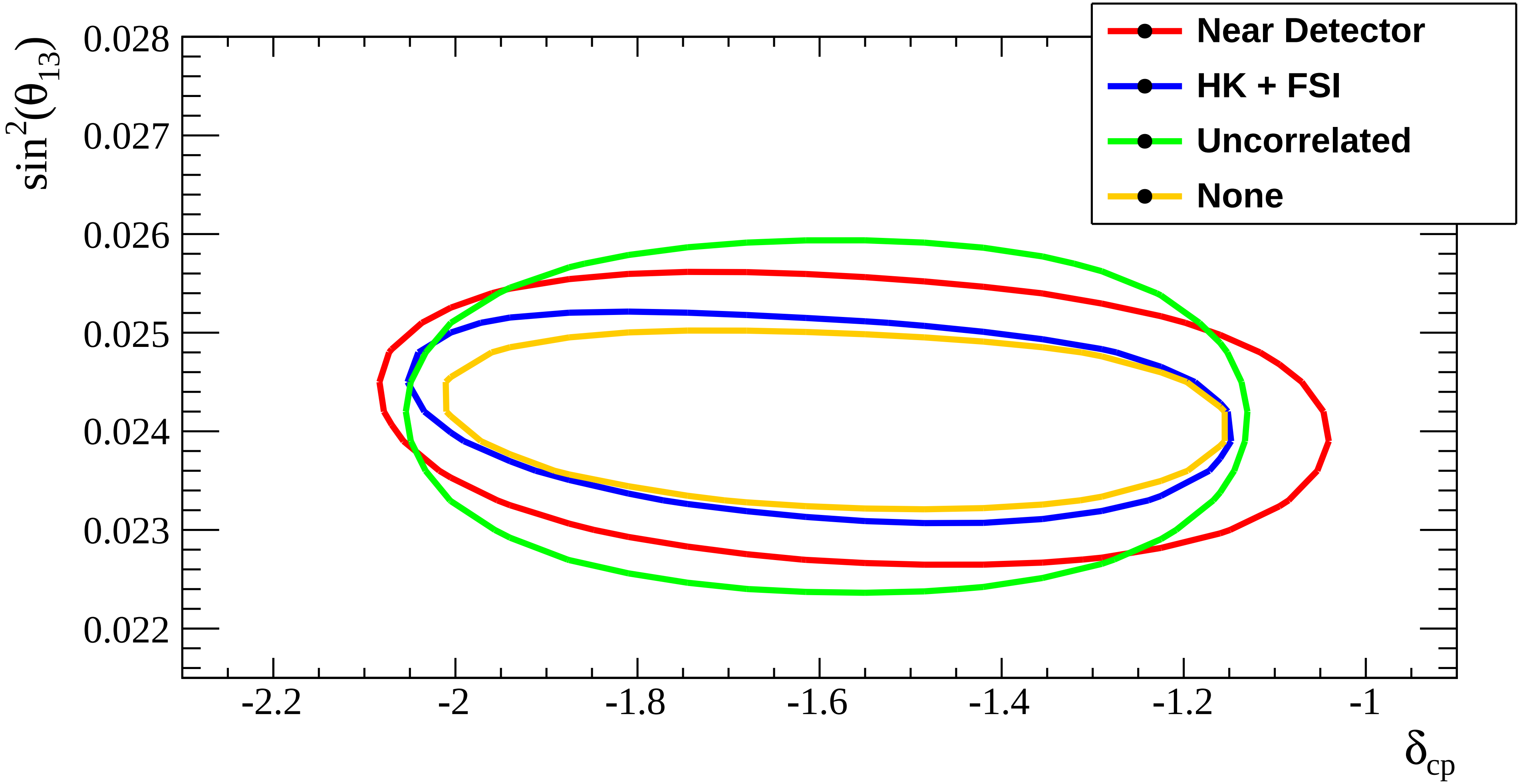
90% confidence interval $sin^2(\theta_{13}) - \delta_{cp}$

Only group of systematic errors in legend allowed to float in the fit. (all others fixed to nominal)



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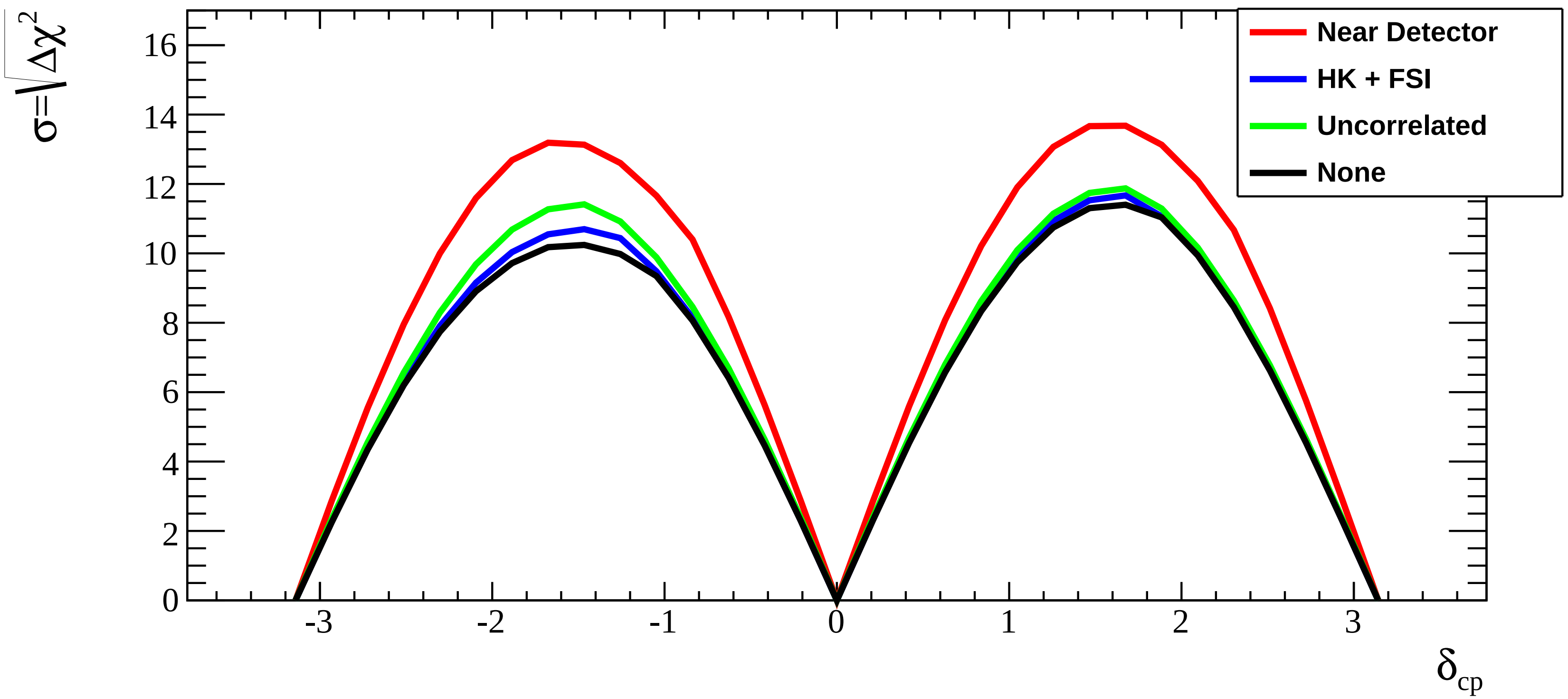
Confidence of rejecting $sin(\delta_{cp}) = 0$ as a function of true δ_{cp}

Effect of constraining groups of systematic errors



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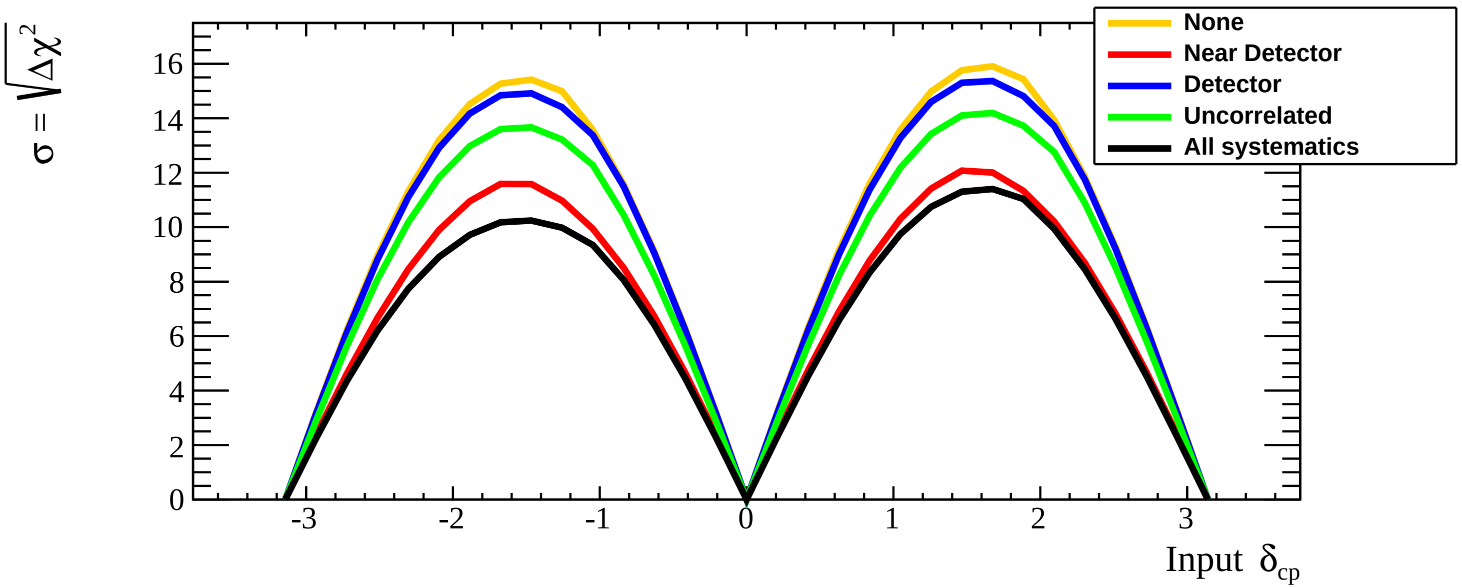

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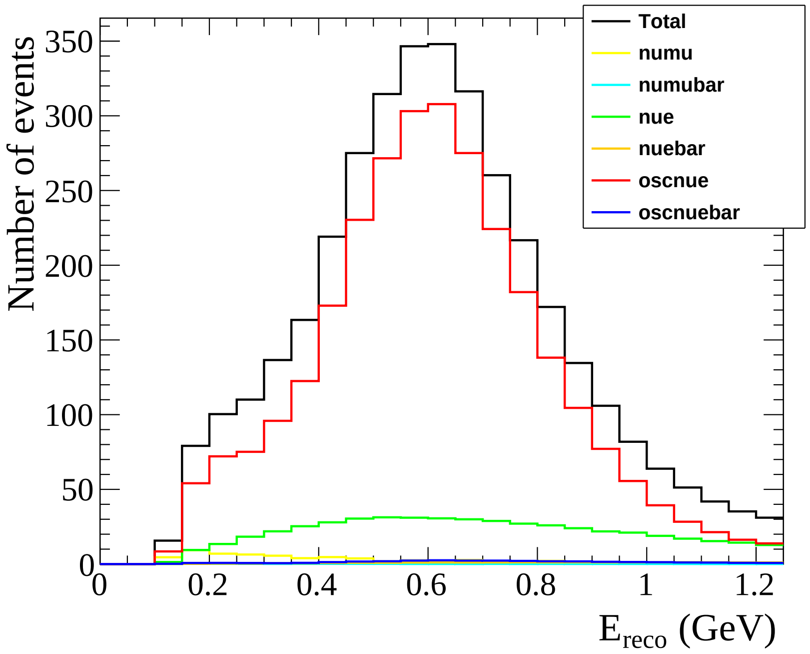
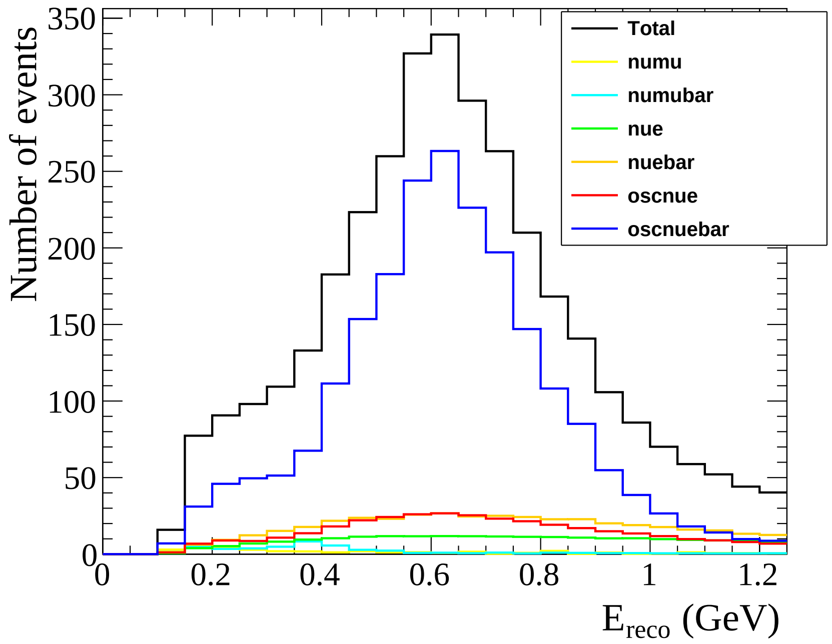
Nominal 1-ring e-like spectra



FHC (neutrino-enhanced)



RHC (antineutrino-enhanced)

$\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{23} = 2.4 \cdot 10^{-3} eV^2$, $\sin^2\theta_{13} = 0.0241$, $\sin^2\theta_{12} = 0.306$, $\Delta m^2_{21} = 7.5 \cdot 10^{-5} eV^2$