# VaLOR Off-Axis angle optimisation studies

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# Outline

- Quick introduction to the VALOR T2K 3-flavour oscillation fit
- Motivation
- $\delta_{cp}$ Discovery sensitivity
- 2D Confidence contours
- Summary

# VALOR 3-flavour analysis

- Joint measurement of: $sin^2\theta_{13}$, $sin^2\theta_{23}$, $\delta_{CP}$ and $\Delta m^2_{32}$
- Implementing the agreed 2013 analysis strategy.
- Analysis uses the *official* T2K 2013 inputs with appropriate scaling (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

## Analysis Setup

- 10 years nominal annual exposure of 7.5 MW $\cdot$ $10^7$ sec $= 1.56 \cdot 10^{22}$ POT
- Assuming $\pm$320kA horn current
- 1:3 FHC-RHC running ratio
- Consider 93 sources of systematic error :
  1. 66 (33 + 33) Near detector correlated for FHC and RHC mode.
  2. 12 uncorrelated cross-section errors 100% correlated between FHC and RHC.
  3. 19 FSI + HK detector errors 100% correlated between FHC and RHC.

# List of systematics considered

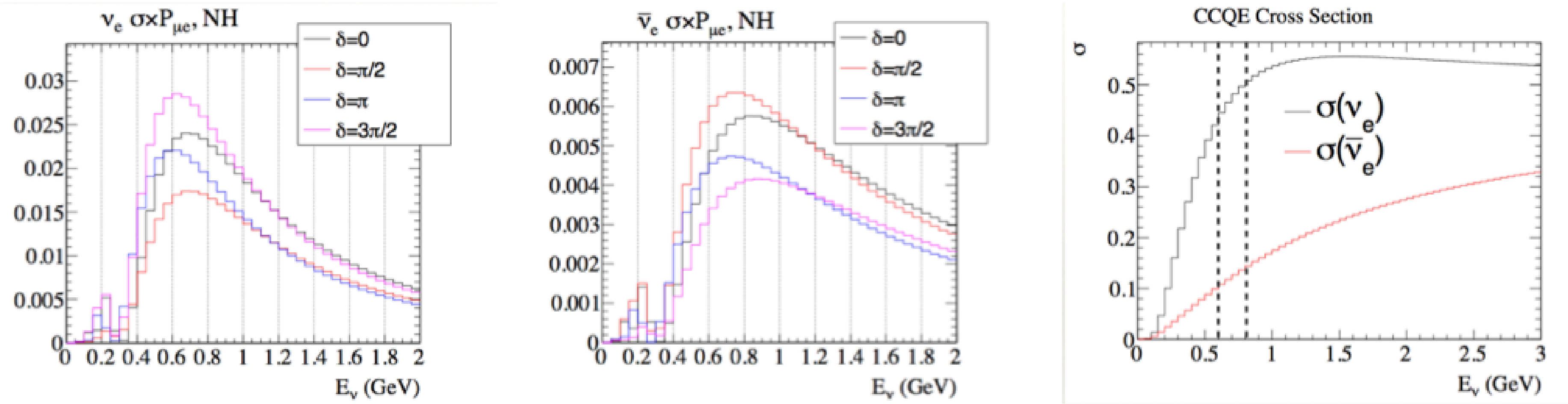
| Type | Systematics | Comment | $N_{syst}$ | $N_{tot}$ |
|---|---|---|---|---|
| ND correlated (FHC) | $f_0^{banff}$ - $f_{24}^{banff}$ | $\nu_\mu$ flux | 11 | |
| | | $\bar{\nu}_\mu$ flux | 5 | |
| | | $\nu_e$ flux | 7 | |
| | | $\bar{\nu}_e$ flux | 2 | |
| | $f_{25}^{banff}$ | CCQE axial mass | 1 | |
| | $f_{26}^{banff}$ | Resonant axial mass | 1 | |
| | $f_{27}^{banff}$-$f_{28}^{banff}$ | CCQE Norm | 3 | |
| | $f_{30}^{banff}$-$f_{31}^{banff}$ | CC1$\pi$ Norm | 2 | |
| | $f_{32}^{banff}$ | NC1$\pi^0$ | 1 | 33 |
| ND correlated (RHC) | FHC * 1.06 | | | 33 |
| Uncorrelated | $f_{WShape}$ | $\pi$ p-distribution (50%) | 1 | |
| | $f_{\pi-less\Delta}$ | $\pi$less $\Delta$ decay (20%) | 1 | |
| | $f_{CCcoh}$ | $\sigma$ CC coherent (50%) | 1 | |
| | $f_{NCoth}$ | $\sigma$ NC other (30%) | 1 | |
| | $f_{NCcoh}$ | $\sigma$ NC coherent (30%) | 1 | |
| | $f_{NC\pi}$ | $\sigma$ NC$\pi$ (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 | |
| | $f_{pF}$ | *FermiMomentum* (14%) | 1 | |
| | $f_{bindE}$ | *Bindingenergy* (30%) | 1 | |
| | $f_{Wshape}$ | *PionMomentum* (52%) | 1 | |
| | $f_{SF}$ | *SpectralFunction* | 1 | 12 |
| (SK+ FSI)/$\sqrt{20}$ | $f_E$ | 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 |

# Motivation

1. Choice of off axis angle can have considerable impact on the beam energy distribution, composition and total flux seen at HK.
2. 2.5 $^\circ$ off-axis beam was optimised for T2K experiment.
   - Discovery of $\theta_{13}$
   - Precise measurements of 23 sector parameters $\Delta m^2_{32}$ and $\theta_{23}$
3. What about HK goals? CP Sensitivity

# Motivation

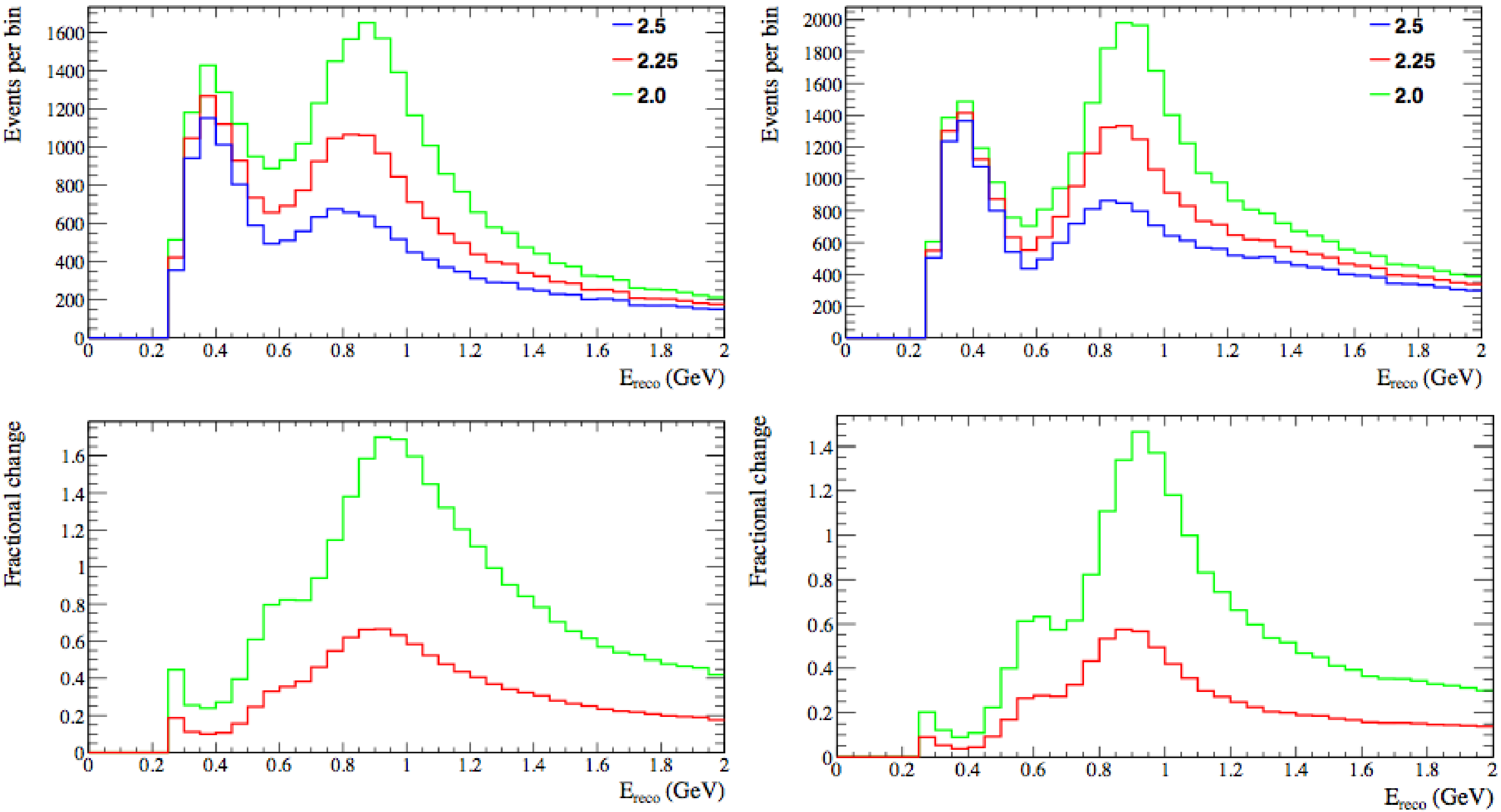
- Current (2.5°) Off-Axis angle spectrum peaks at 0.6 GeV
- CCQE Cross section is rising in this region
- $\sigma_e$ x appearance probability for $\bar{\nu}_e$ (and $\nu_e$ also rising)



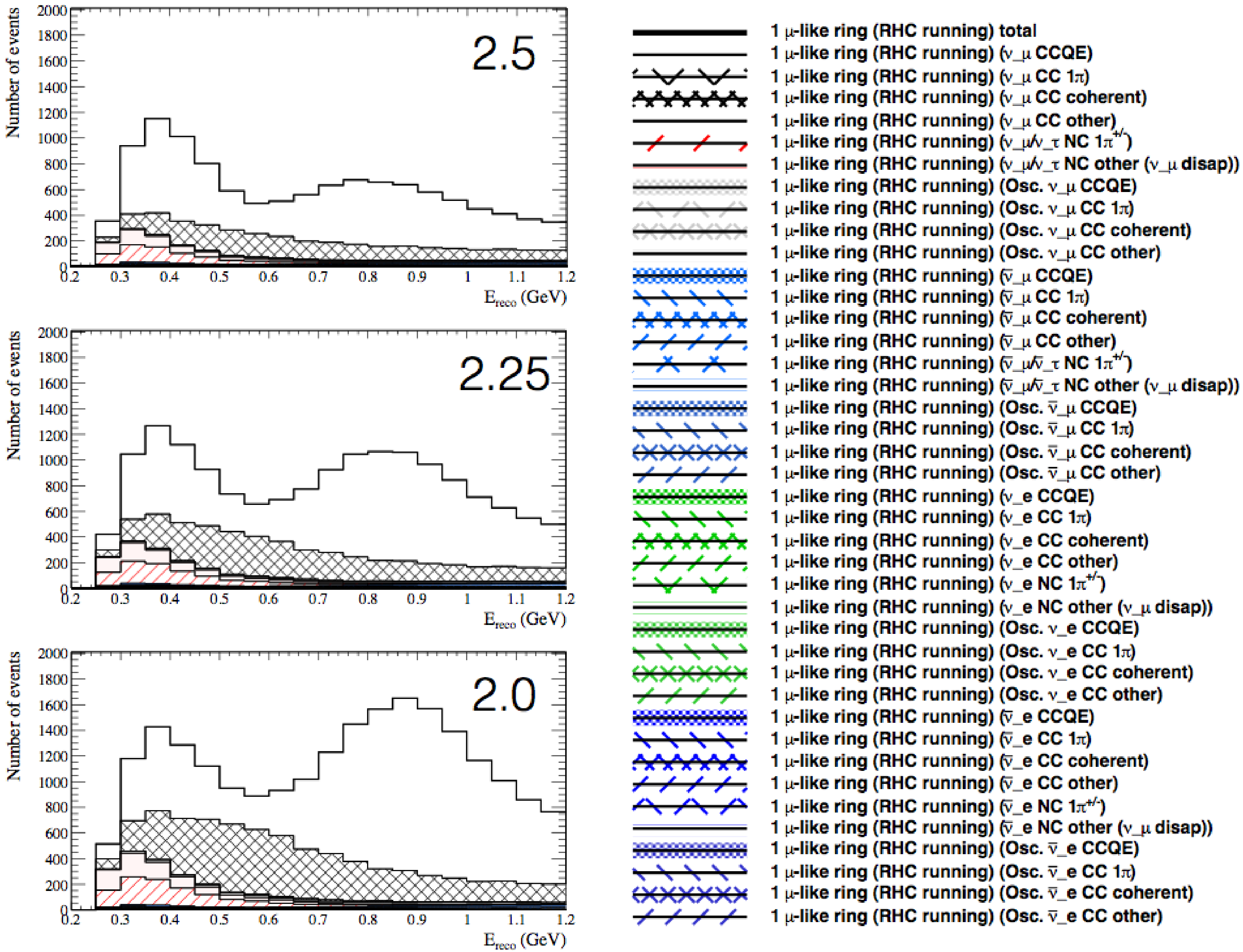

- On axis beam can lead to improved statistics
- Studied the effect of moving to 2.25 and 2.0 degrees off axis

# $1R_\mu$ Spectra

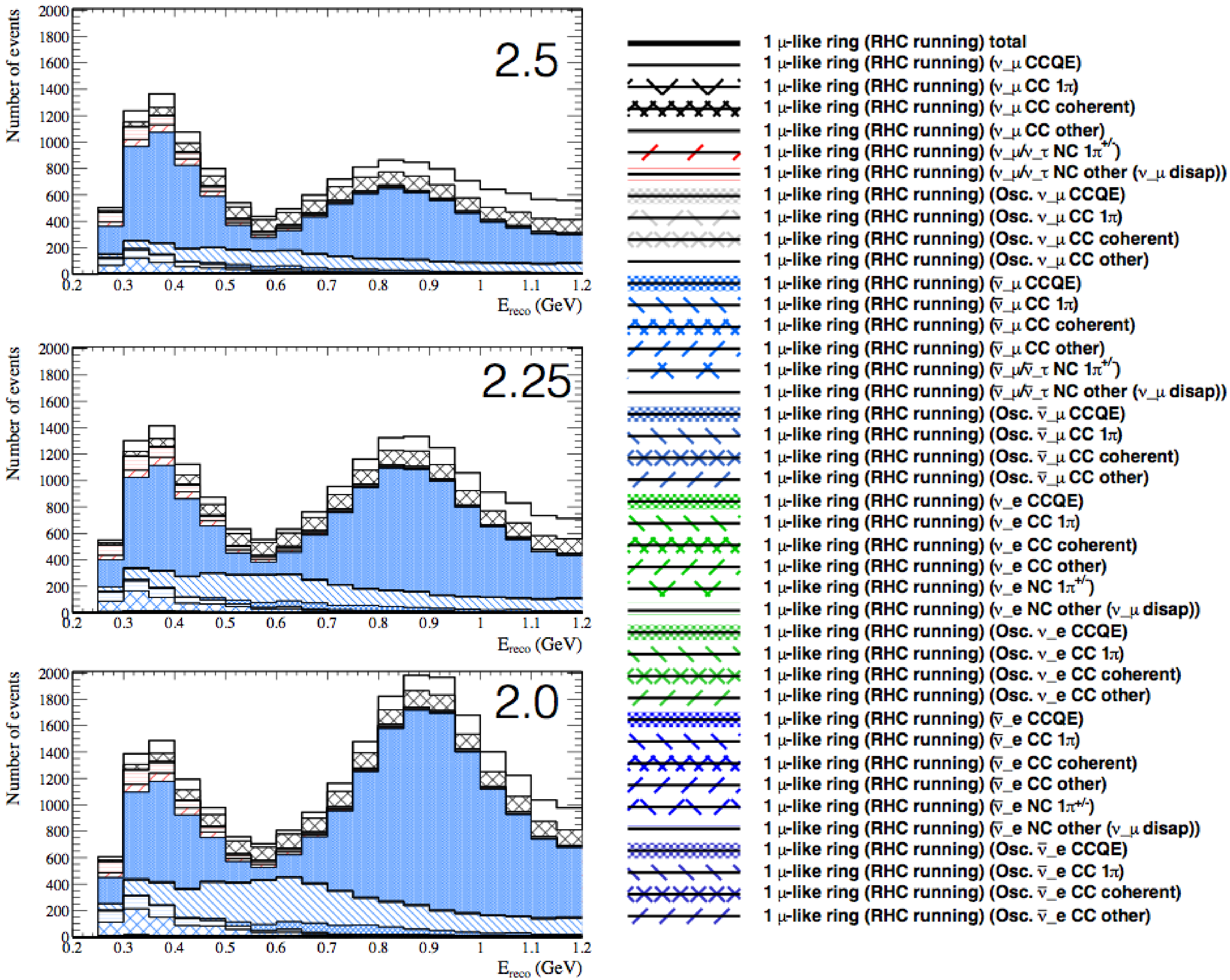
**FHC** **RHC**

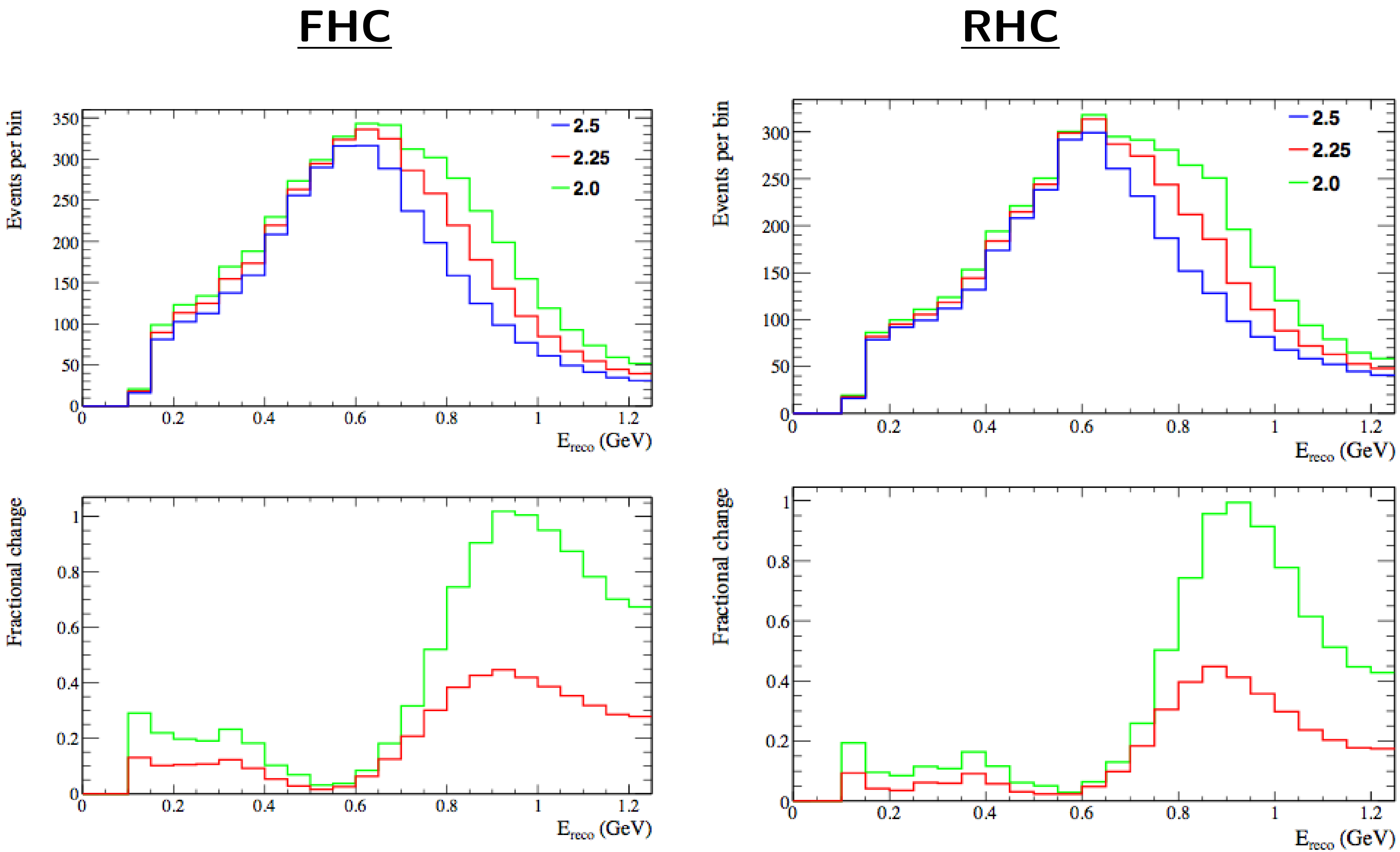


# $1R_\mu$ FHC Spectra

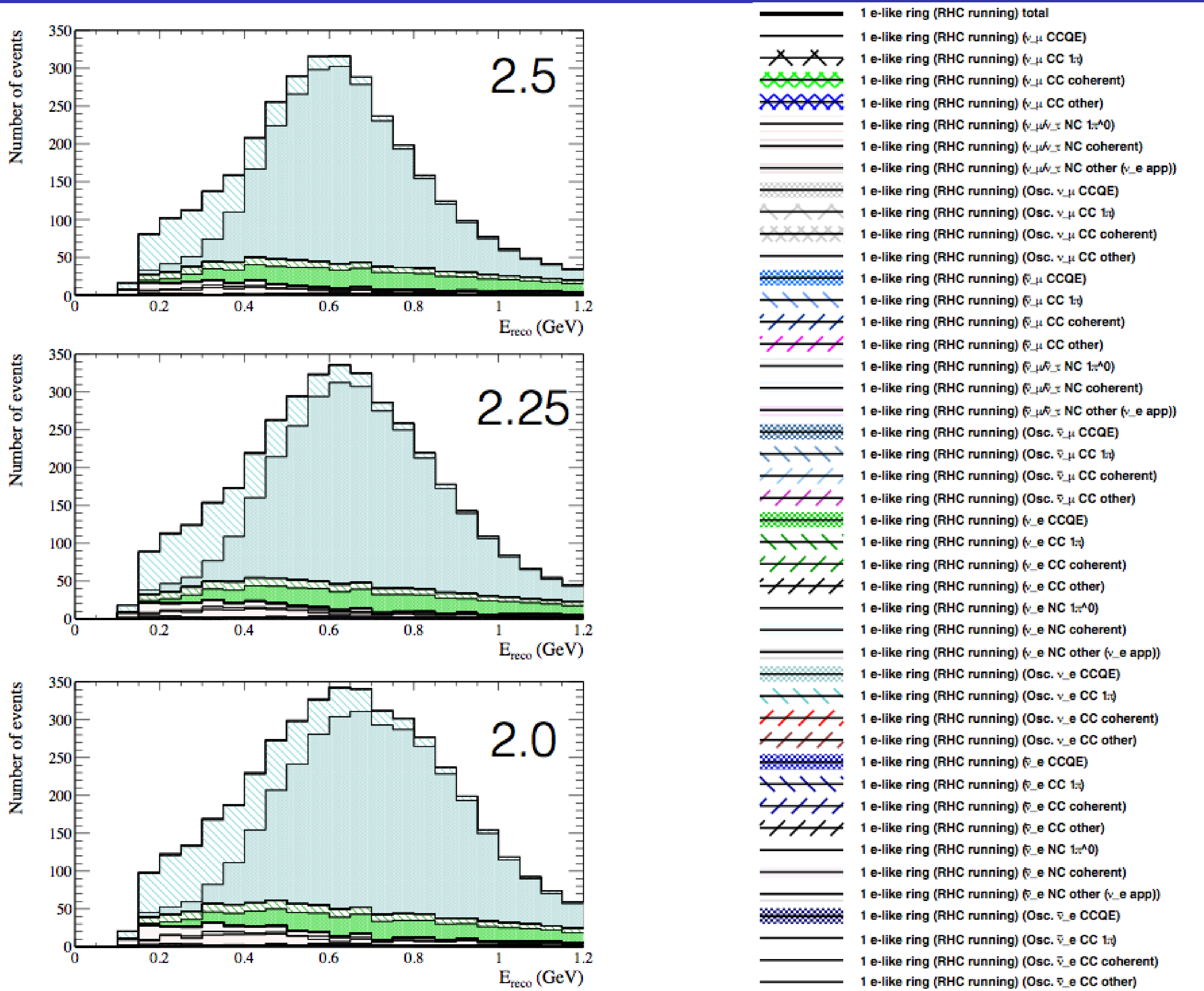


# $1R_\mu$ RHC Spectra

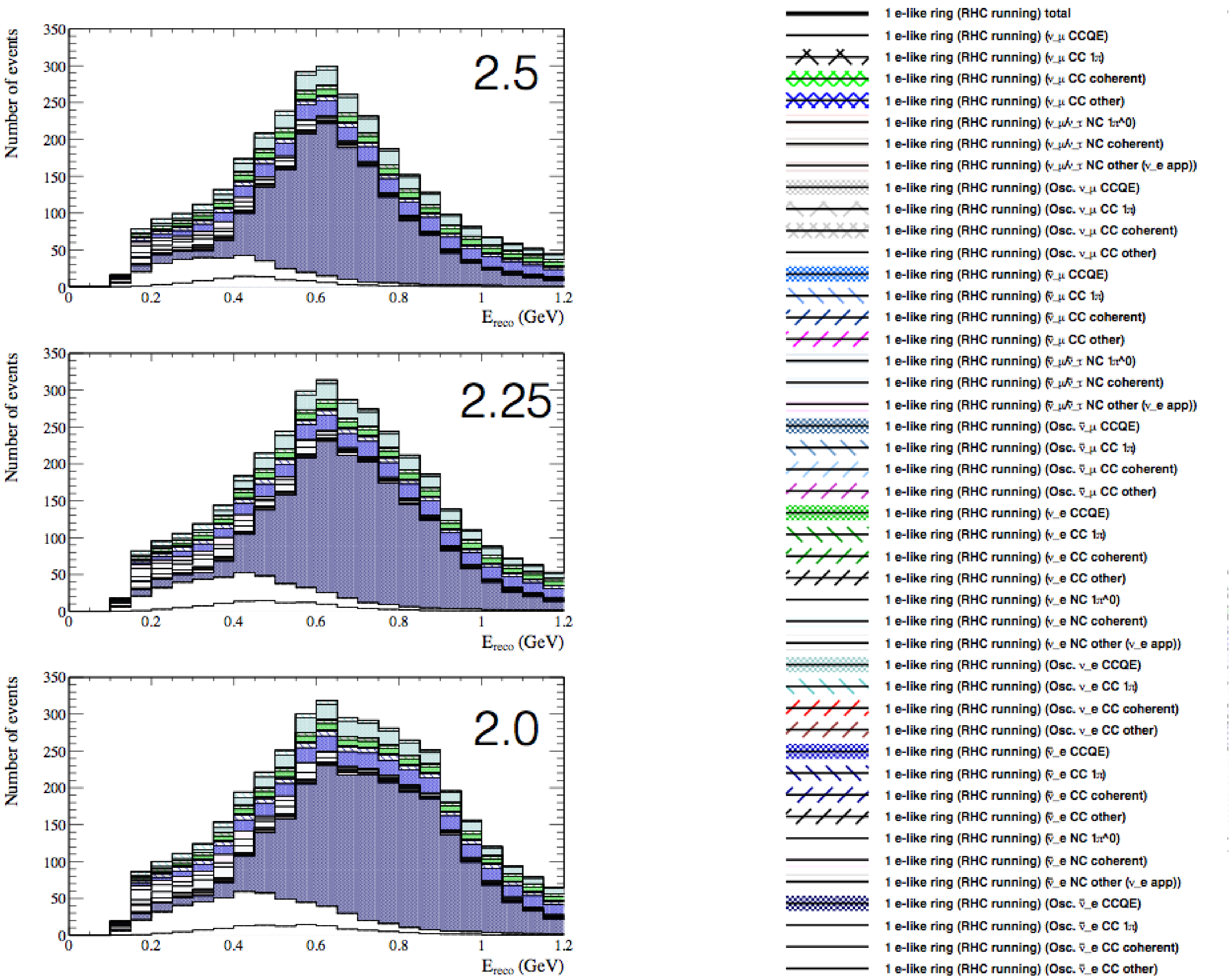



FHC
RHC
Events per bin
Fractional change
2.5
2.25
2.0
$E_{reco}$ (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
50
100
150
200
250
300
350

# $1R_e$ FHC Spectra



# $1R_e$ RHC Spectra

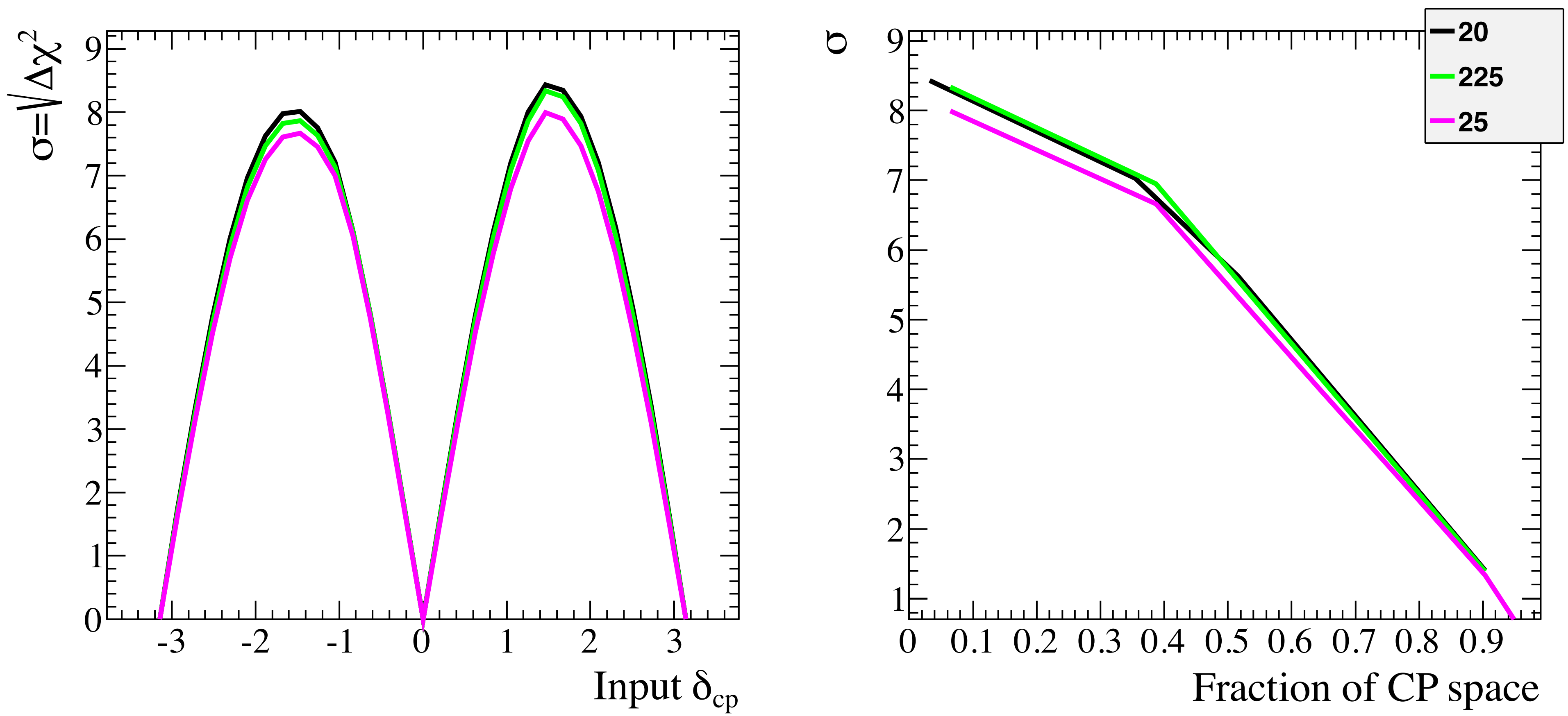


# $\delta_{cp}$ Sensitivity Studies

- *Create MC spectra for given value of* $\delta_{CP}$
- *Do multiple fits to determine* $\chi^2_{min}(sin(\delta_{CP}) = 0)$
  - *Do fits with* $\delta_{CP} = \pi, 0$
  - *Do each fit with true hierarchy*
- $\Delta\chi^2 = \chi^2_{BestFit} - \chi^2_{True}$
- *Plotted* $\Delta\chi^2$ *for each value of* $\delta_{cp}$

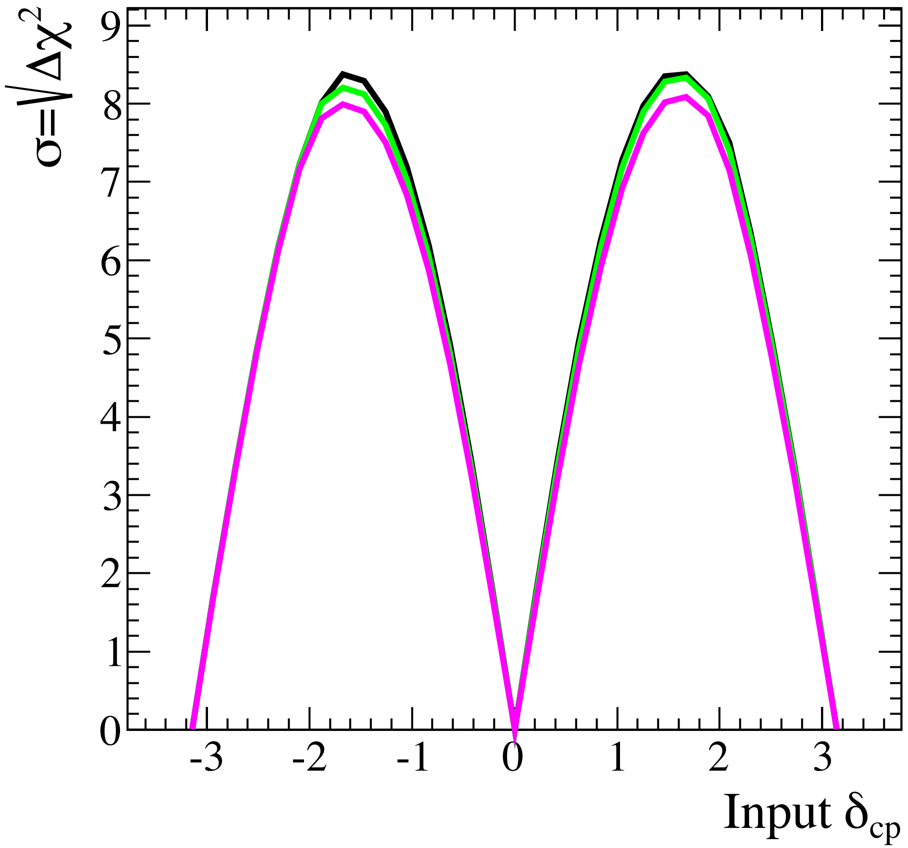
- Studies assumed 10yr HK data ($1.56 \times 10^{22} pot$)
- True oscillation parameters:
  $sin^2(\theta_{13}) = 0.0241, sin^2(\theta_{23}) = 0.5, sin^2(\theta_{12}) = 0.306,$
  $\Delta m^2_{21} = 7.5 \cdot 10^{-5} eV^2, \Delta m^2_{32} = 2.4 \cdot 10^{-3} eV^2$

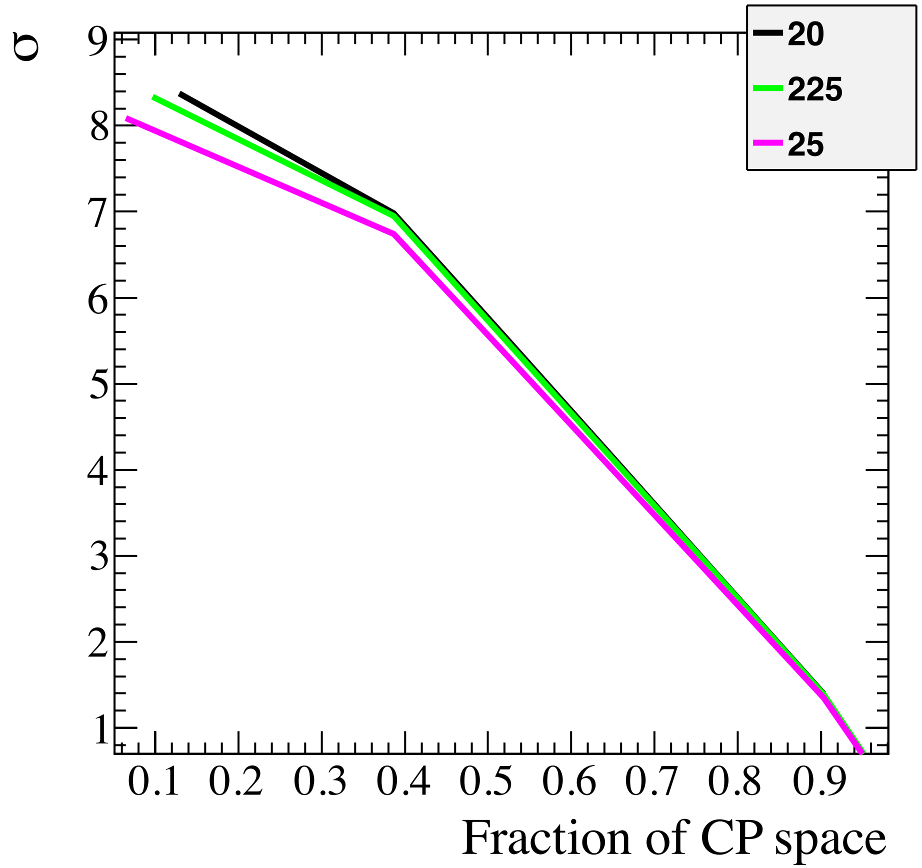
# $\delta_{cp}$ Sensitivity Studies - True Normal Hierarchy




$$sin^2(\theta_{13}) = 0.0241, sin^2(\theta_{23}) = 0.5, sin^2(\theta_{12}) = 0.306,$$
$$\Delta m^2_{21} = 7.5 \cdot 10^{-5} eV^2, \Delta m^2_{32} = 2.4 \cdot 10^{-3} eV^2$$

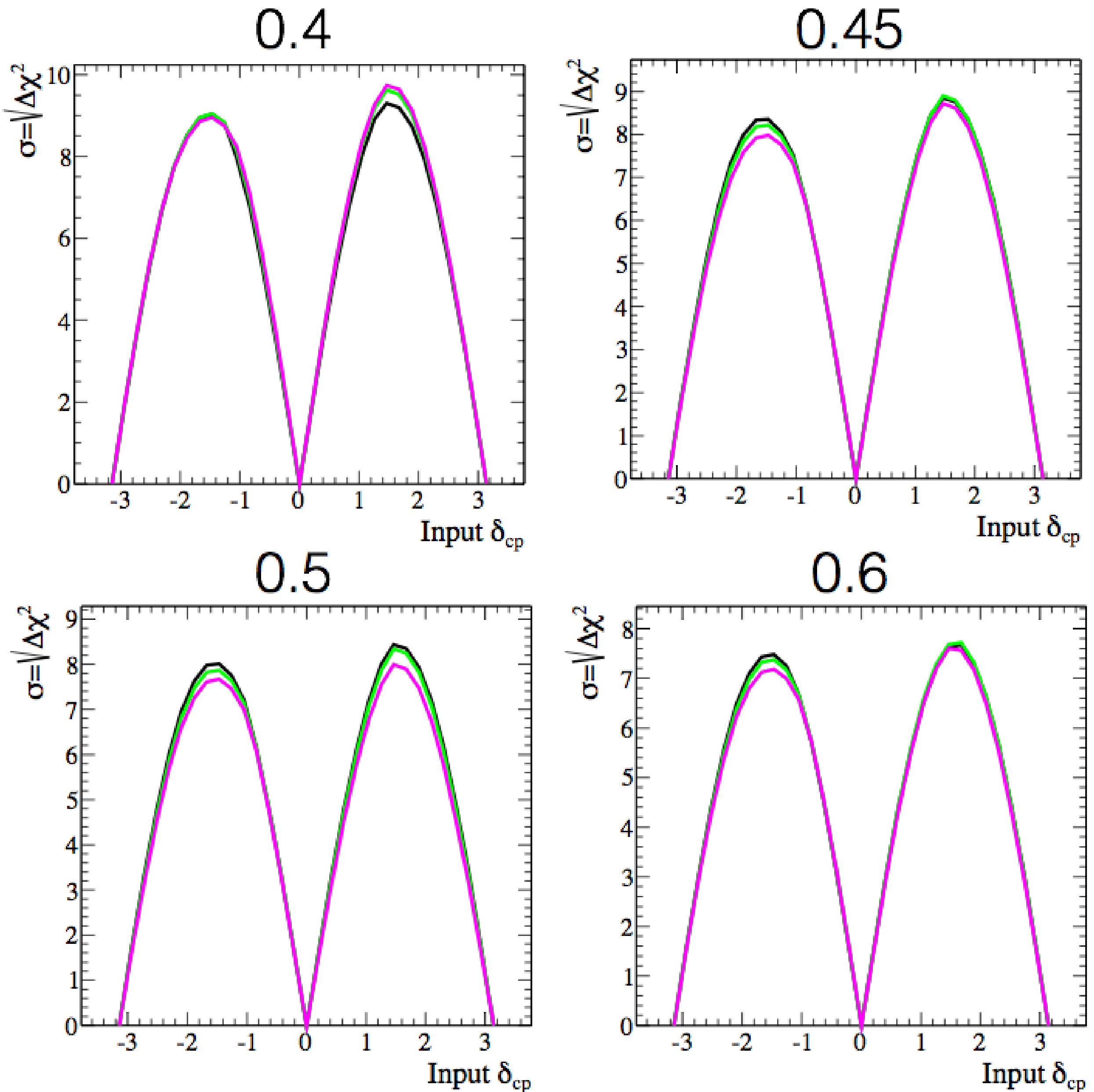
# $\delta_{cp}$ Sensitivity Studies - True Inverted Hierarchy



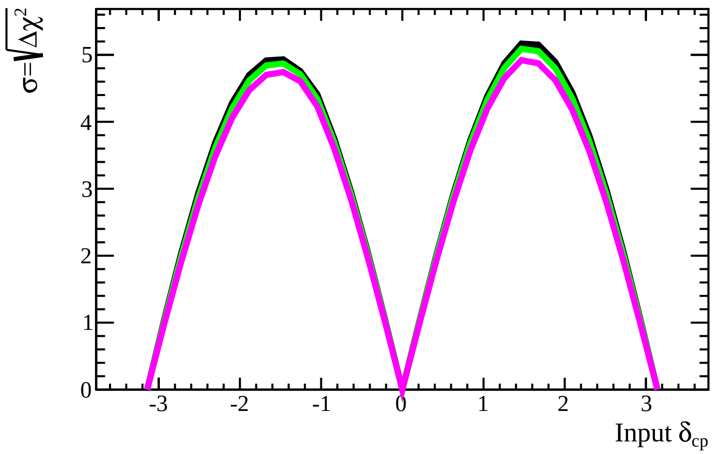



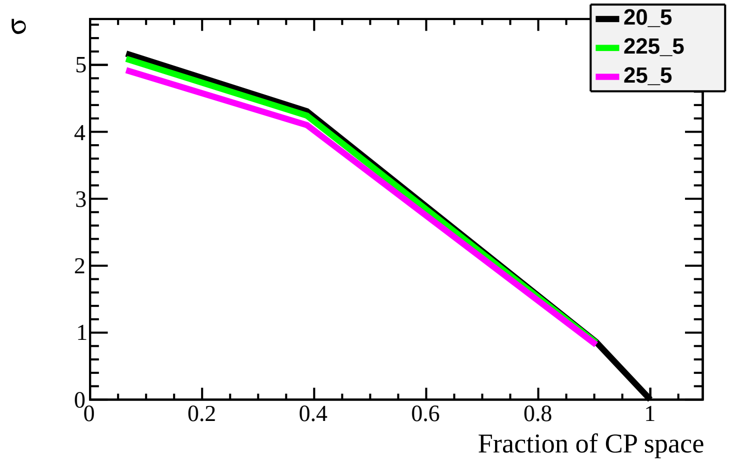

$$sin^2(\theta_{13}) = 0.0241, sin^2(\theta_{23}) = 0.5, sin^2(\theta_{12}) = 0.306,$$
$$\Delta m^2_{21} = 7.5 \cdot 10^{-5} eV^2, \Delta m^2_{32} = 2.4 \cdot 10^{-3} eV^2$$

# $\delta_{cp}$ Sensitivity Studies - $sin^2(\theta_{23})$ Dependance

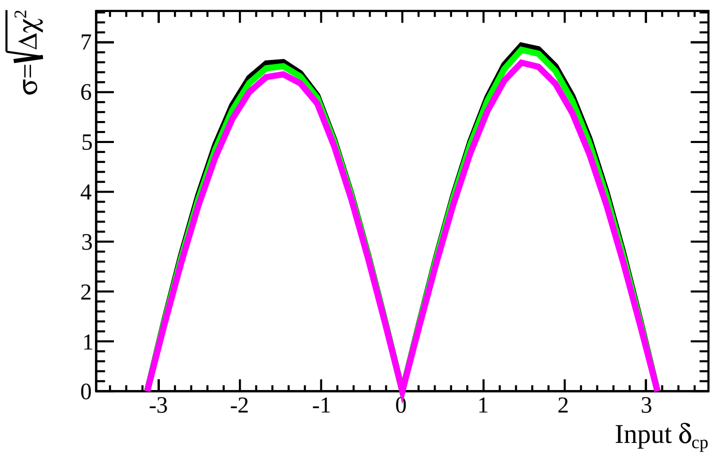


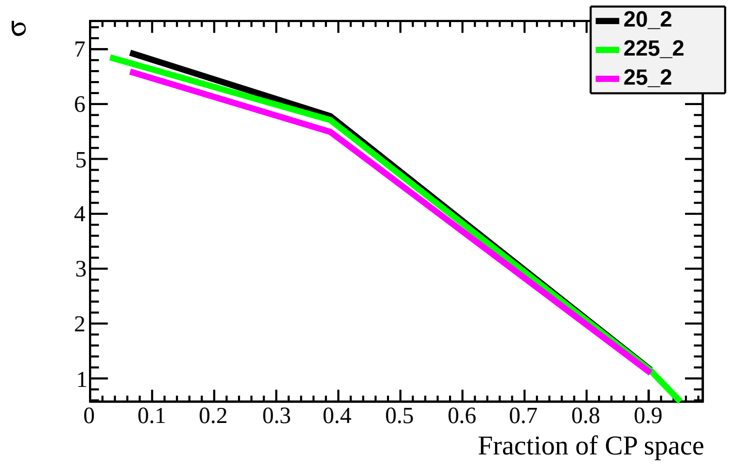
**20%**



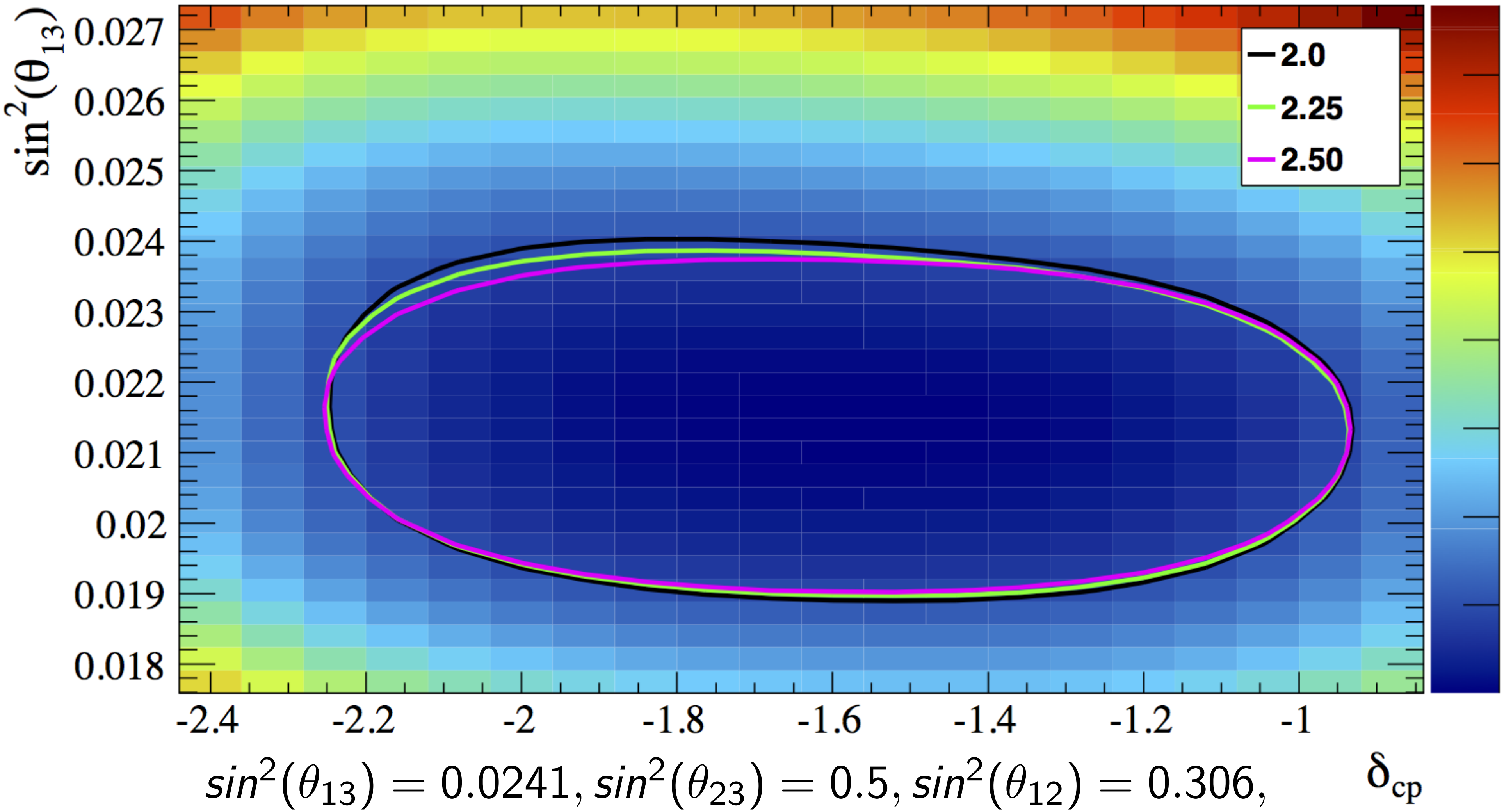

**50%**




$$sin^2(\theta_{13}) = 0.0241, sin^2(\theta_{23}) = 0.5, sin^2(\theta_{12}) = 0.306,$$
$$\Delta m^2_{21} = 7.5 \cdot 10^{-5} eV^2, \Delta m^2_{32} = 2.4 \cdot 10^{-3} eV^2, NH$$

# Sensitivity- 2D Contours $sin^2(\theta_{13})$-$\delta_{cp}$ (90% Confidence)

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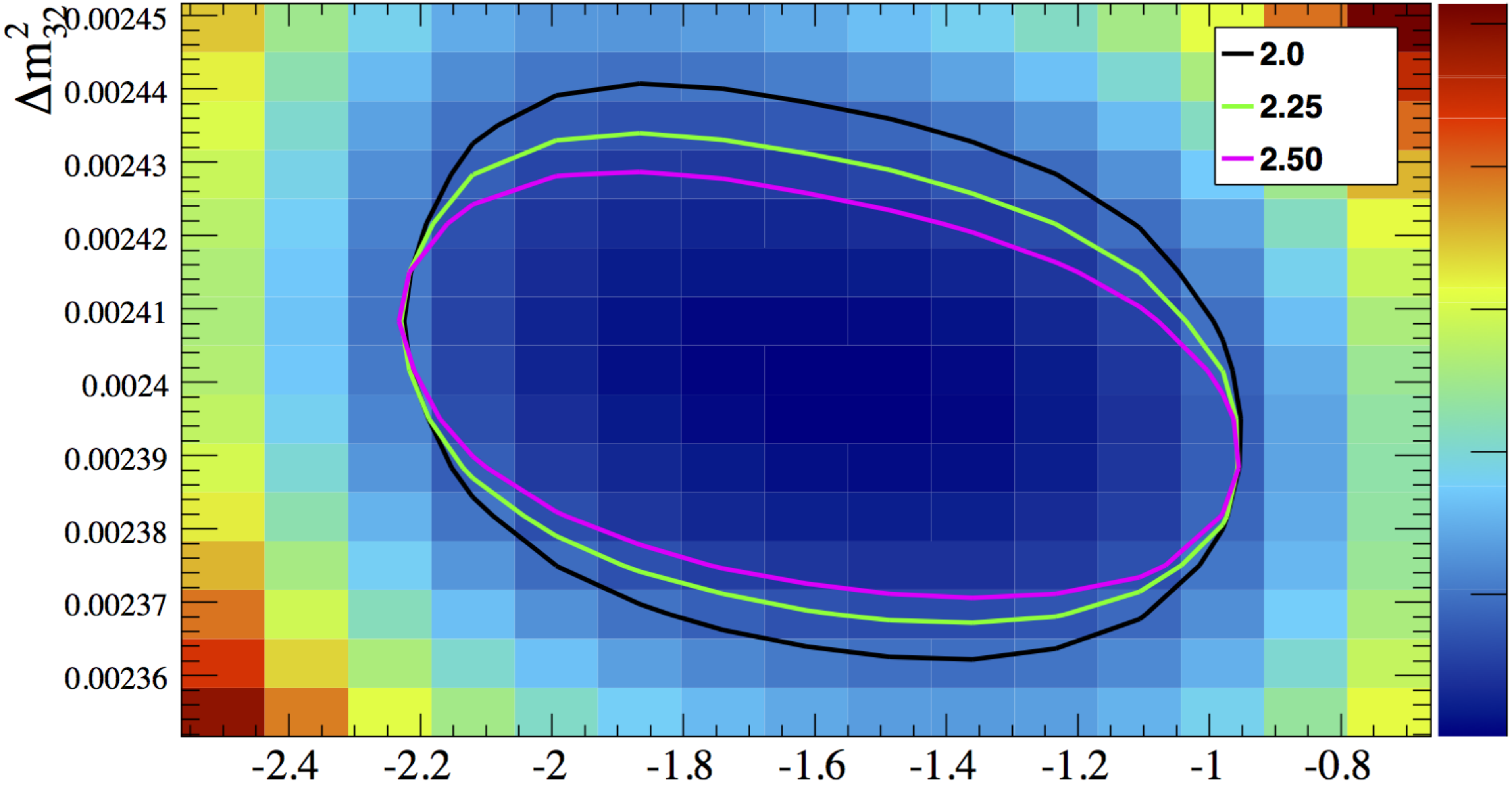
# Sensitivity- 2D Contours $\delta_{cp}$-$\Delta m^2_{32}$ (90% Confidence)

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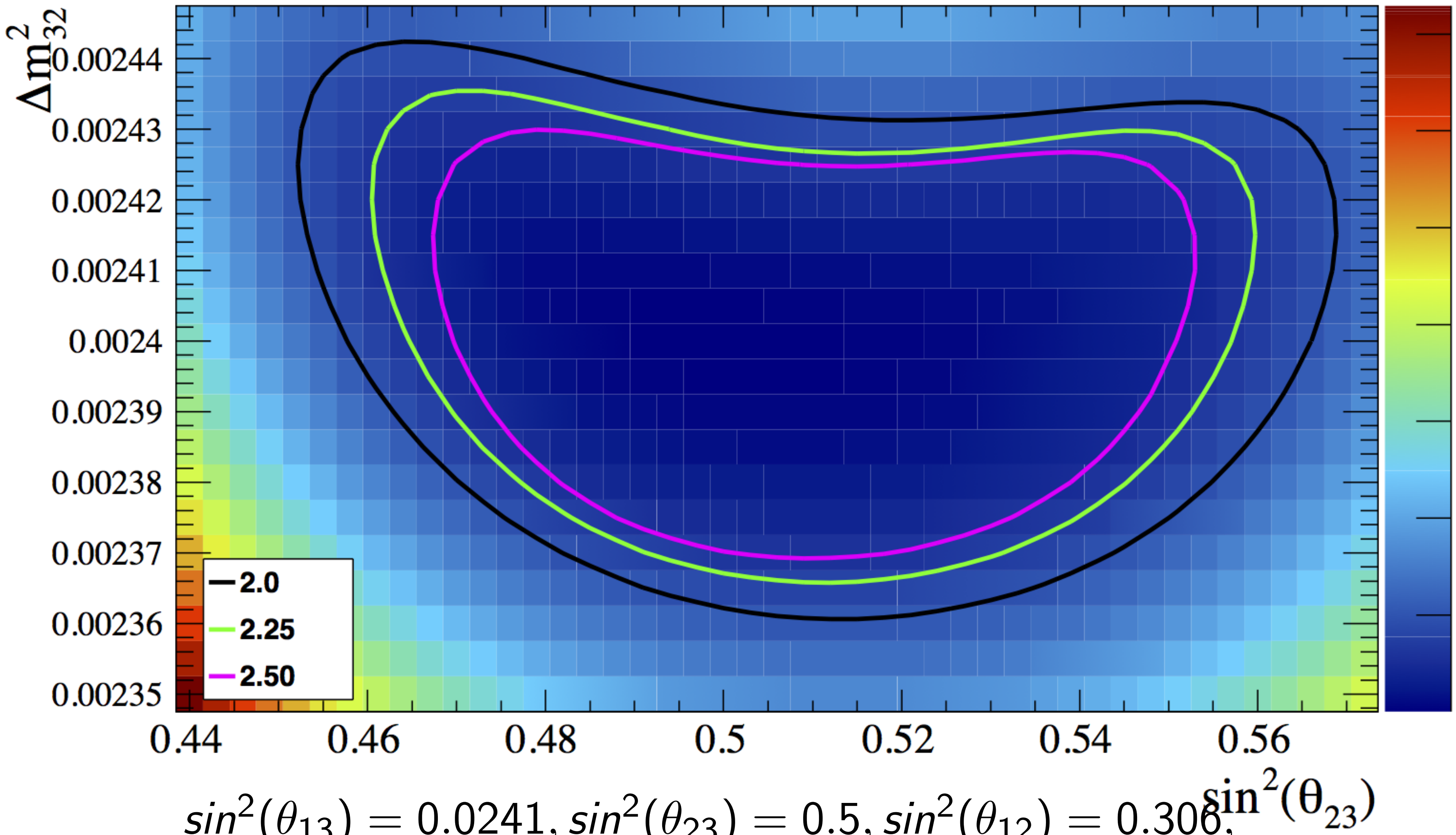
# Sensitivity-2D Contours $sin^2(\theta_{23})$-$\Delta m^2_{32}$ (90% Confidence)



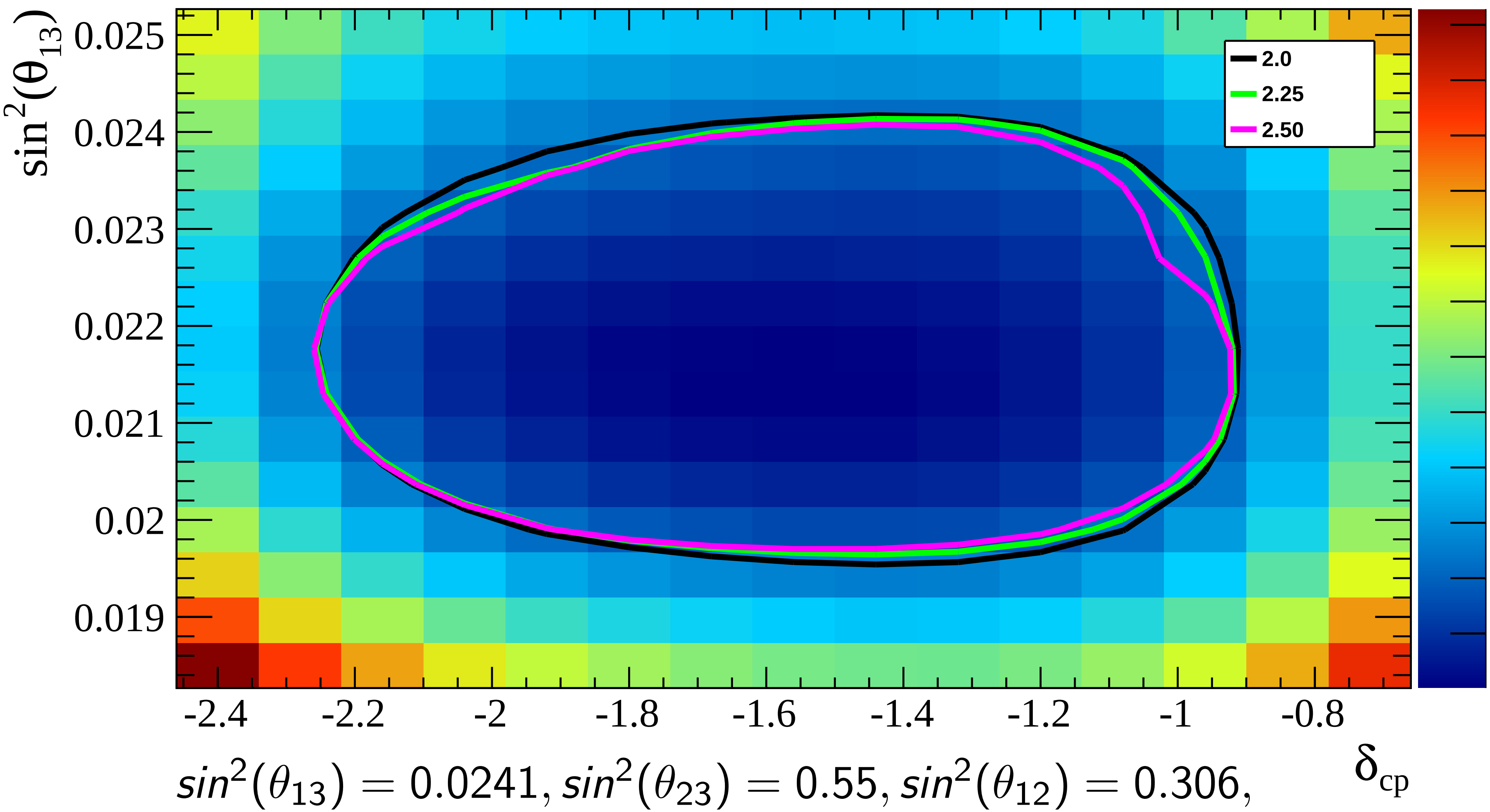

$$sin^2(\theta_{13}) = 0.0241, sin^2(\theta_{23}) = 0.5, sin^2(\theta_{12}) = 0.306,$$
$$\Delta m^2_{21} = 7.5 \cdot 10^{-5} eV^2, \Delta m^2_{32} = 2.4 \cdot 10^{-3} eV^2, \delta_{cp} = -\frac{\pi}{2}$$

# Summary

- Moving on axis has a much larger effect on 23 sector due to background around oscillation dip
- $\delta_{cp}$ discovery potential unchanged when moving on axis
- No difference when systematics or statistics limited

Backup Slides

# Sensitivity- 2D Contours $sin^2(\theta_{13})$-$\delta_{cp}$ (90% Confidence)




$sin^2(\theta_{13}) = 0.0241, sin^2(\theta_{23}) = 0.55, sin^2(\theta_{12}) = 0.306,$
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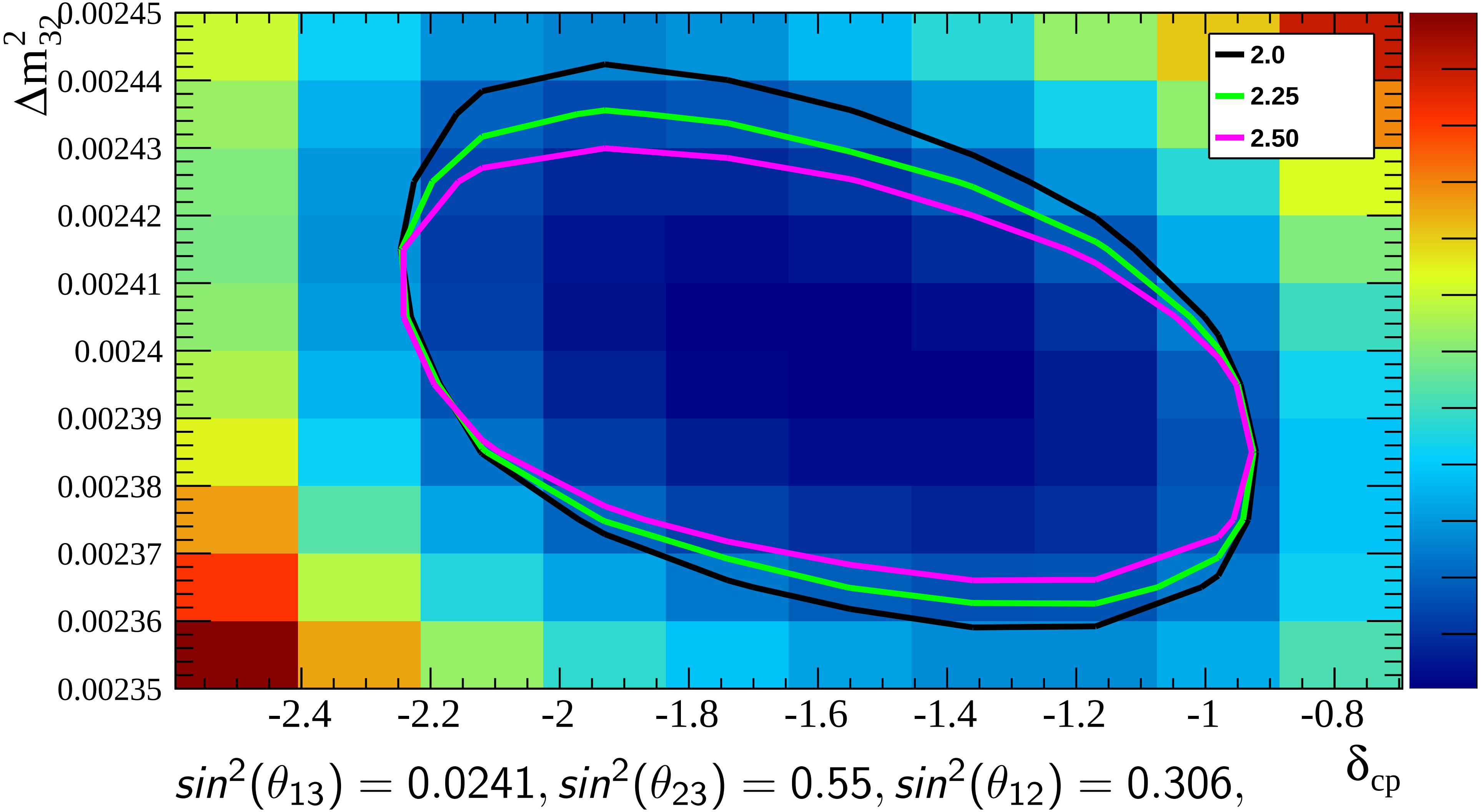
# Sensitivity- 2D Contours $\delta_{cp}$-$\Delta m^2_{32}$ (90% Confidence)

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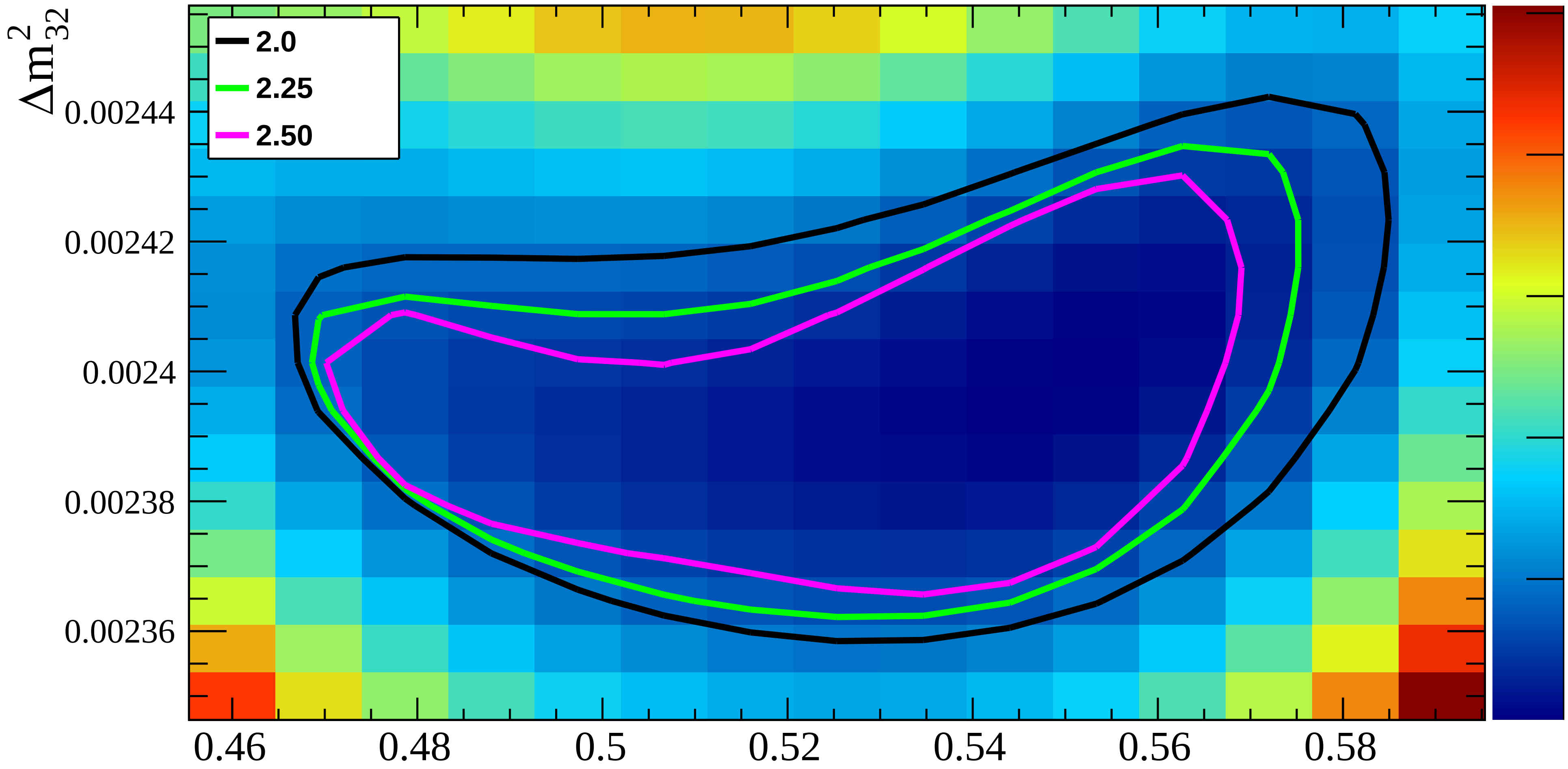
# Sensitivity-2D Contours $sin^2(\theta_{23})$-$\Delta m^2_{32}$ (90% Confidence)

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