DUNE Oscillation Physics: Bayesian Sensitivity Studies

Liban Warsame for the DUNE collaboration
liban.warsame@stfc.ac.uk
UKRI STFC Rutherford Appleton Laboratory

NuFact 2024 - Argonne National Laboratory, Chicago
17/09/2024

Science and Technology Facilities Council

DUNE Physics Goals

DUNE has a **rich** physics program which includes:

1. Make precise measurements of the oscillation parameters θ_{23}, θ_{13} and Δm_{32}^2
2. Resolve the neutrino mass hierarchy, i.e. whether $m_3^2 > m_2^2$ or $m_3^2 < m_2^2$
3. Determine the octant of θ_{23}
4. Determine whether CP is violated in neutrinos and make a measurement of δ_{CP}
5. Search for τ appearance
6. Check the unitarity of the PMNS matrix
7. Search for nucleon decay
8. Be ready to detect low-energy neutrinos from a supernova
9. Search for Beyond Standard Model physics, e.g. sterile neutrinos, heavy neutral leptons etc .

DUNE Physics Goals

DUNE has a **rich** physics program which includes:

1. Make precise measurements of the oscillation parameters θ_{23}, θ_{13} and Δm_{32}^2
2. Resolve the neutrino mass hierarchy, i.e. whether $m_3^2 > m_2^2$ or $m_3^2 < m_2^2$
3. Determine the octant of θ_{23}
4. Determine whether CP is violated in neutrinos and make a measurement of δ_{CP}
5. Search for τ appearance
6. Check the unitarity of the PMNS matrix
7. Search for nucleon decay
8. Be ready to detect low-energy neutrinos from a supernova
9. Search for Beyond Standard Model physics, e.g. sterile neutrinos, heavy neutral leptons etc .

This talk will focus on **(1-4)**

UKRI Science and Technology Facilities Council DUNE

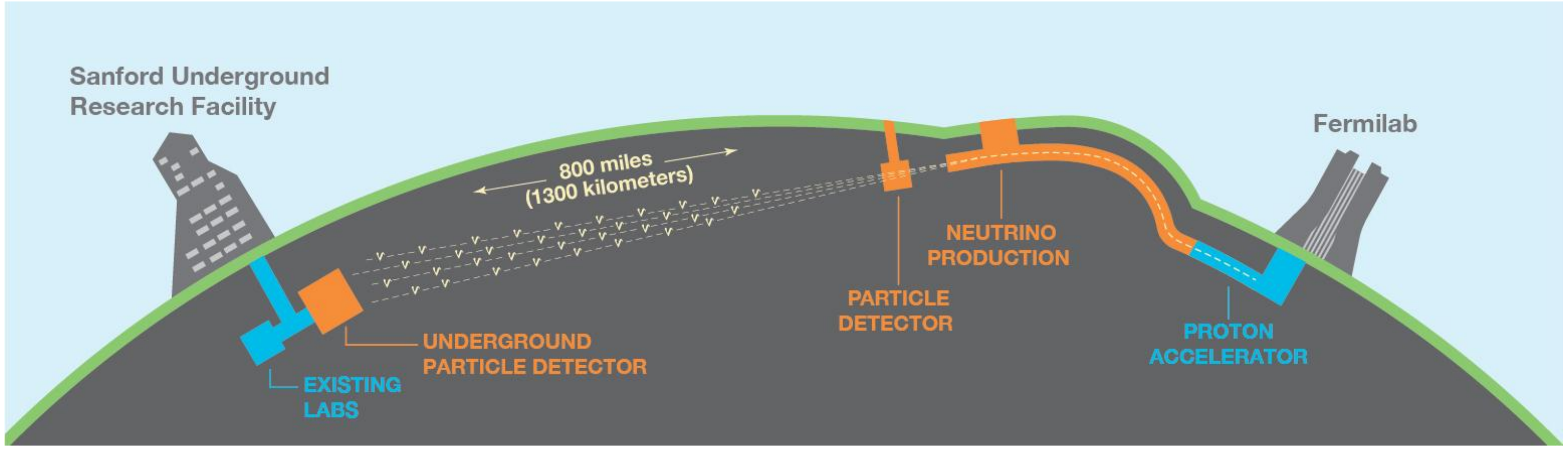
DUNE Collaboration

The DUNE experiment is a large international collaboration with > 1400 collaborators from > 200 institutions in 35 countries

DUNE collaboration meeting January 2023

Deep Underground Neutrino Experiment

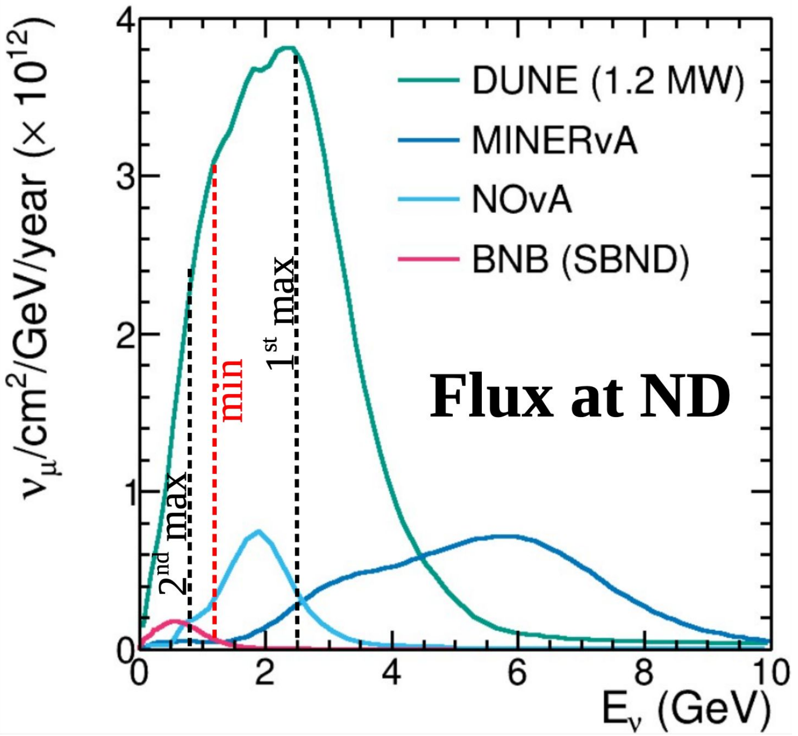
- DUNE will make a beam of predominantly ν_μ or $\overline{\nu}_\mu$ at Fermilab
- Beam passes through near detector **574 m** from target
- Beam passes through far detector **1300 km** from target at Sanford Underground Research Facility (SURF) **1500m** underground

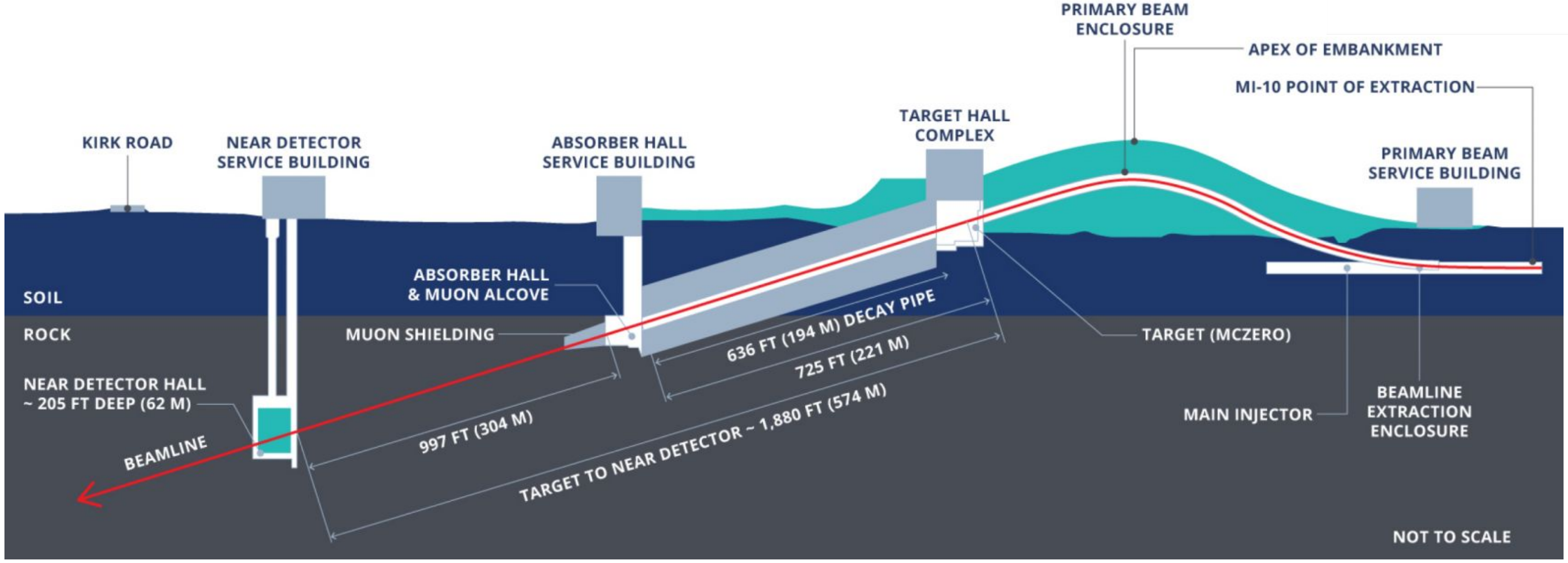


Neutrino beam

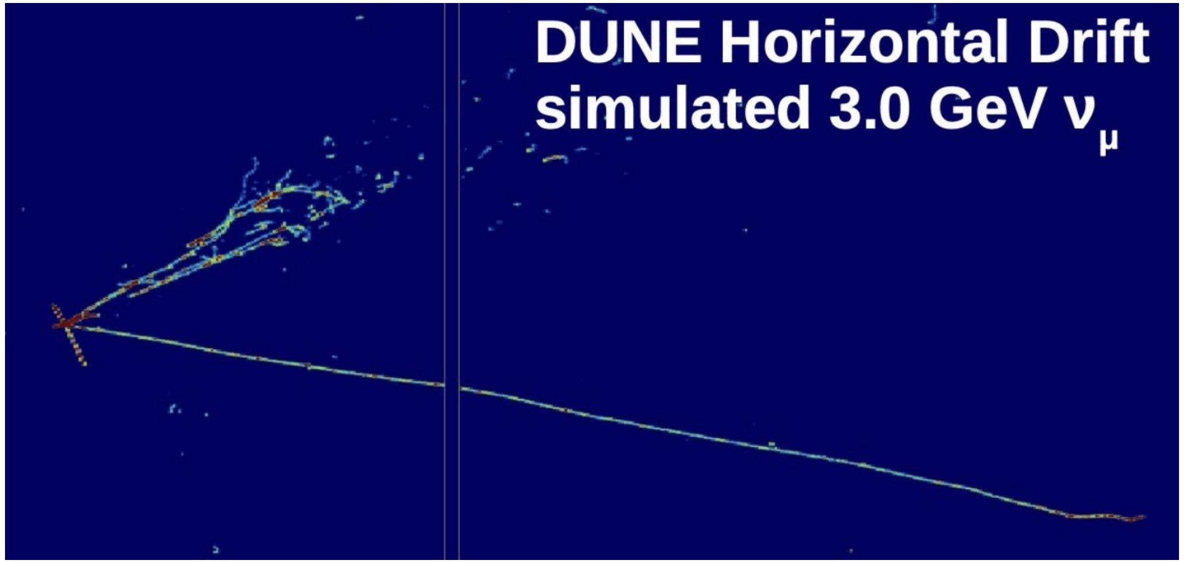
- LBNF beamline will produce **world-leading intensity**
  - Phase 1: **1.2 MW**
  - Phase 2: Upgrade to → **2 MW**

- On-axis beam —> broad range of energies
  - Covers **1st & 2nd oscillation maxima**



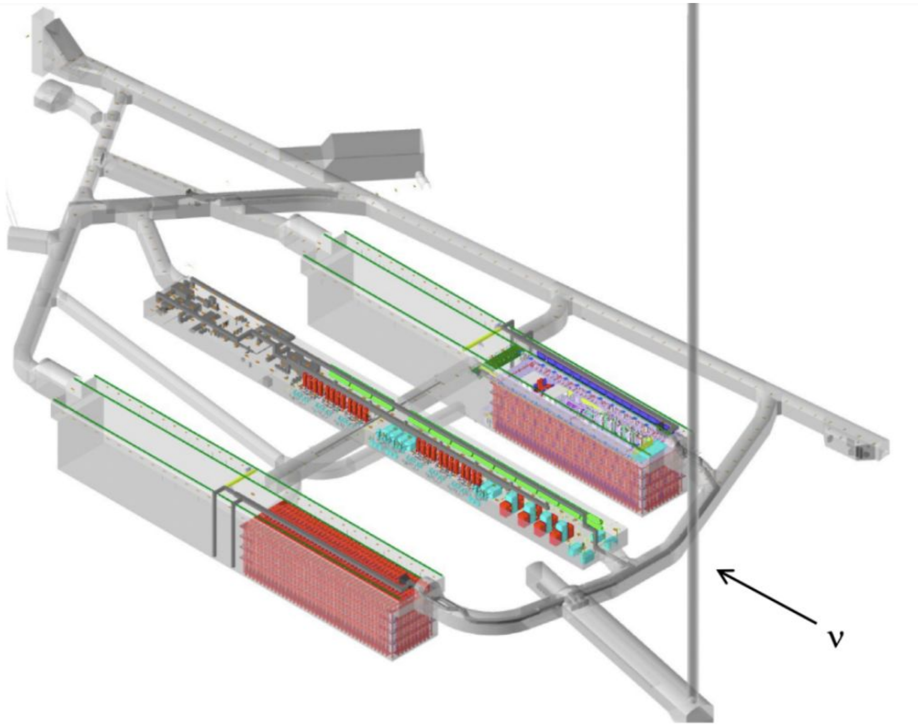


Far detector (FD)



- Liquid argon provides **precise reconstruction** of lepton and hadronic energy over **a broad energy range**

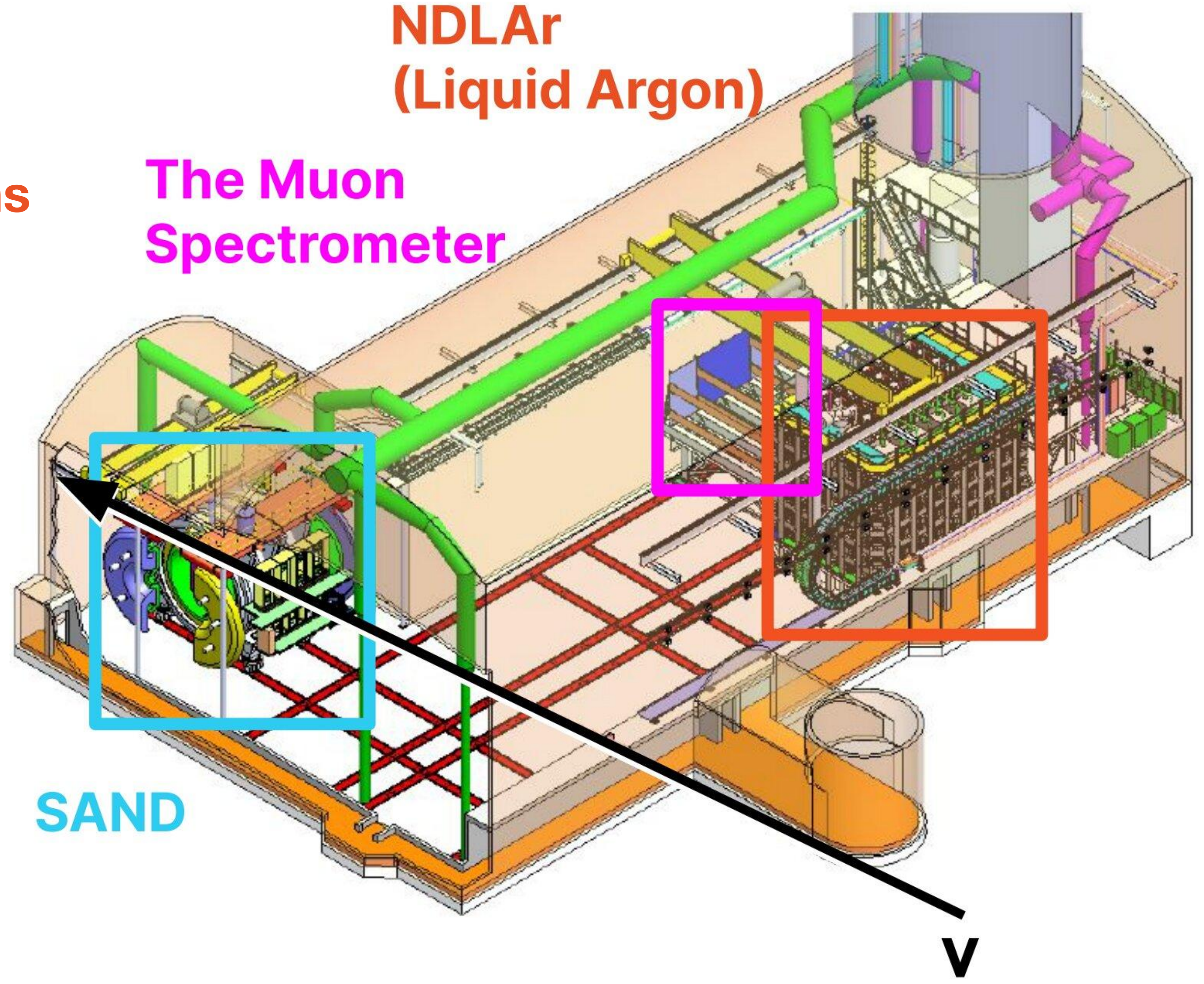
- Will consist of **4 modules:**
  - First module will be a **vertical drift (VD)** LArTPC
  - Second module will be **horizontal drift (HD)**



- VD is the baseline design for Module 3 & 4

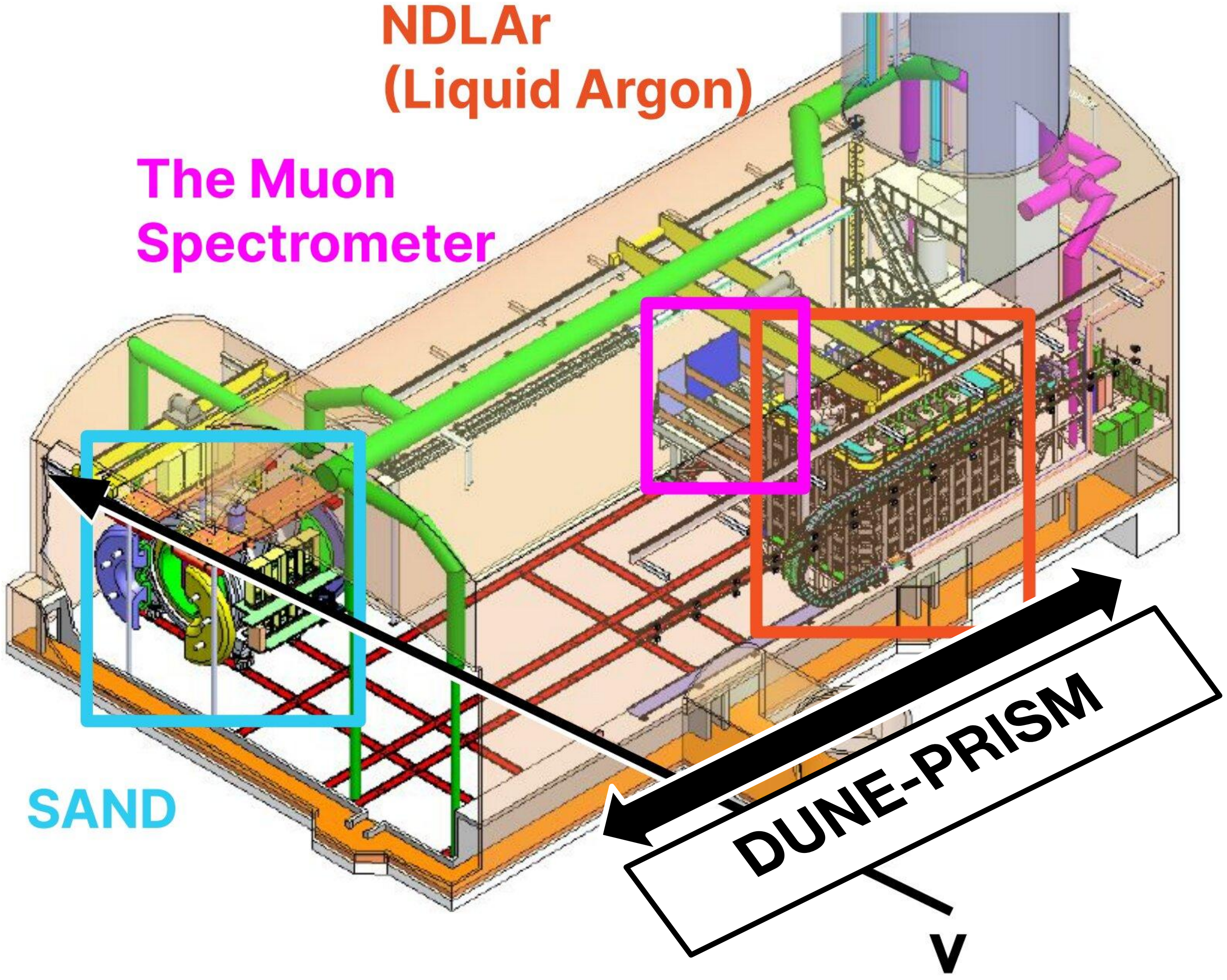
Near detector (ND)

- **ND-LAr:**
  - LAr target → constrain ***ν* - Ar interactions**
  - High event rates → Native 3D readout + optical modularity
- **TMS:**
  - Muon momentum & sign selection
  - Phase II → **GArTPC**
  - Lower threshold → better tracking of low energy particles → deeply probe ***ν* - Ar interactions**
- **SAND:**
  - Beam Monitoring
  - Carbon Target



Near detector (ND)

- **DUNE-PRISM:**
  - Use off-axis effect to sample **multiple fluxes** using the same detectors
  - Allows **isolation** of flux, cross-section and detector effects on rate



See Ciaran Hasnip's talk!

How do long-baseline analyses work?

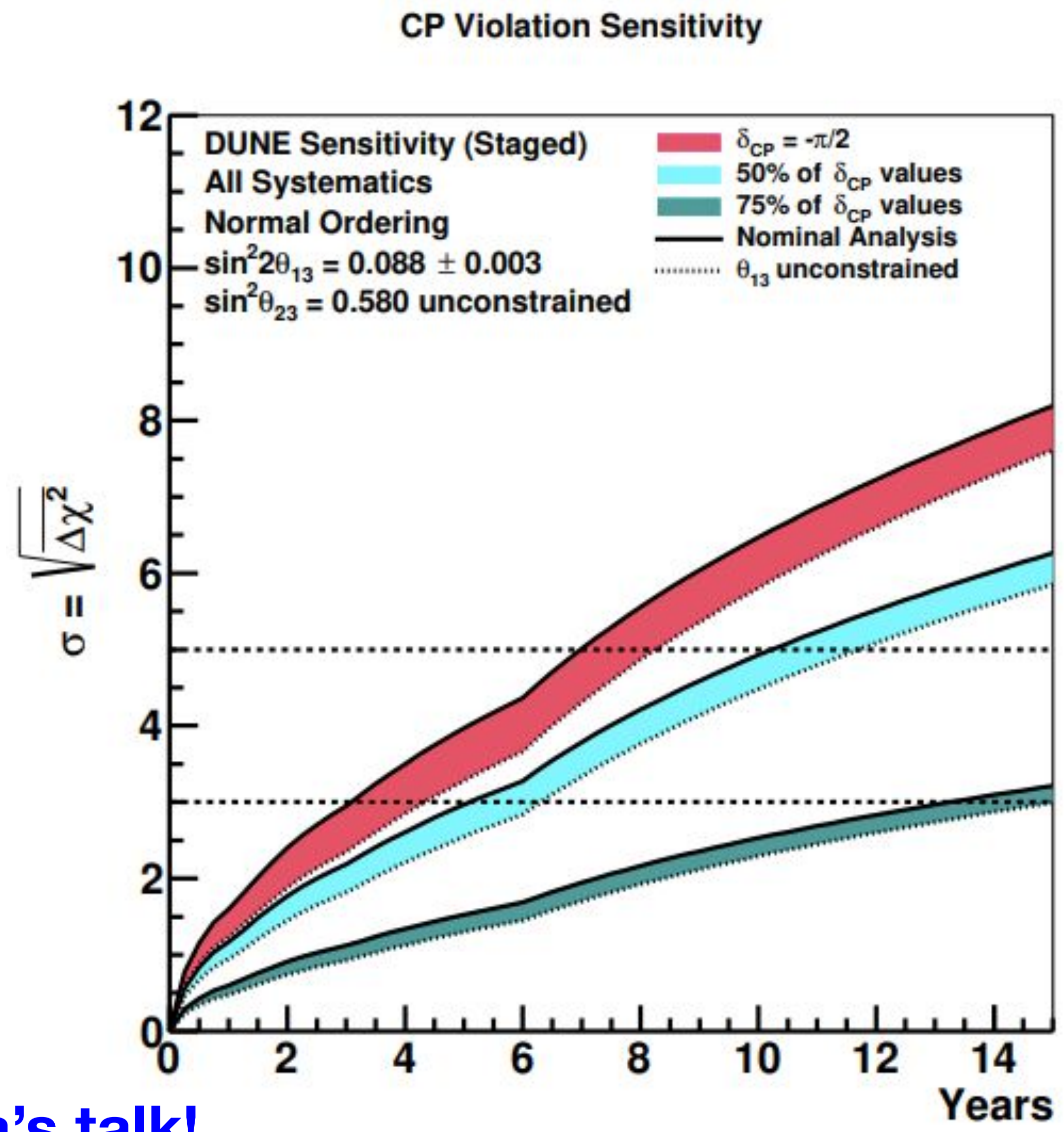
$$N(\text{Observables}) = \int \text{Flux}(E_\nu, \text{time}) \times \text{Interaction prob}(E_\nu, \text{final state}) \times \text{Detector Efficiency}(\text{final state}) \times \text{Osc}(E_\nu)$$

- Measure event rates → product of **oscillations** and **flux/interaction/detector models**
- Near detector has lots of events and assumed to have **no oscillations** → **constrain the systematics**
- Far detector has oscillations → **apply systematic constraints** →**infer oscillation parameter values**

Science and Technology Facilities Council

FD TDR Analysis

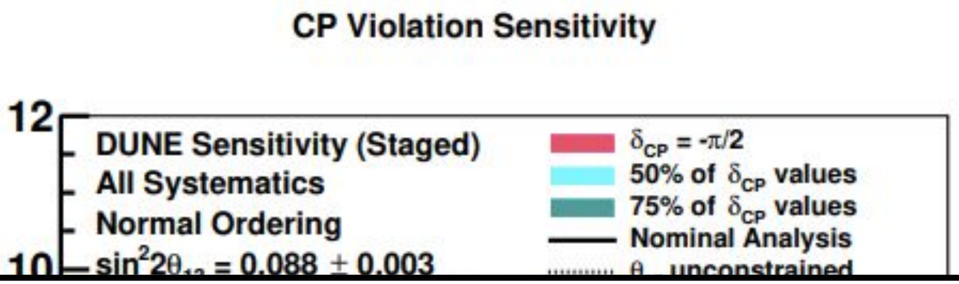
- Current DUNE sensitivities produced using frequentist framework
- Used **4 sample fit** of FD data along with a constraint from the ND
- Far detector samples use full simulation and reconstruction
- Full results available in “Long-baseline neutrino oscillation physics potential of the DUNE experiment” – Eur. Phys. J. C 80, 978 (2020)



[See Meghna Bhattacharya’s talk!]

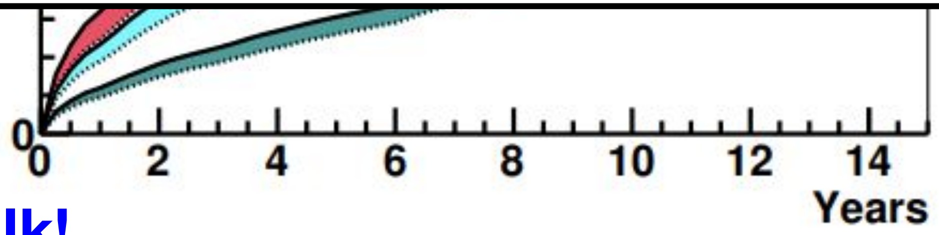
FD TDR Analysis

- Current DUNE sensitivities produced using frequentist framework



This talk focuses on **new Bayesian sensitivity studies** using a Markov Chain Monte Carlo framework

neutrino oscillation physics potential of the DUNE experiment" – Eur. Phys. J. C 80, 978 (2020)

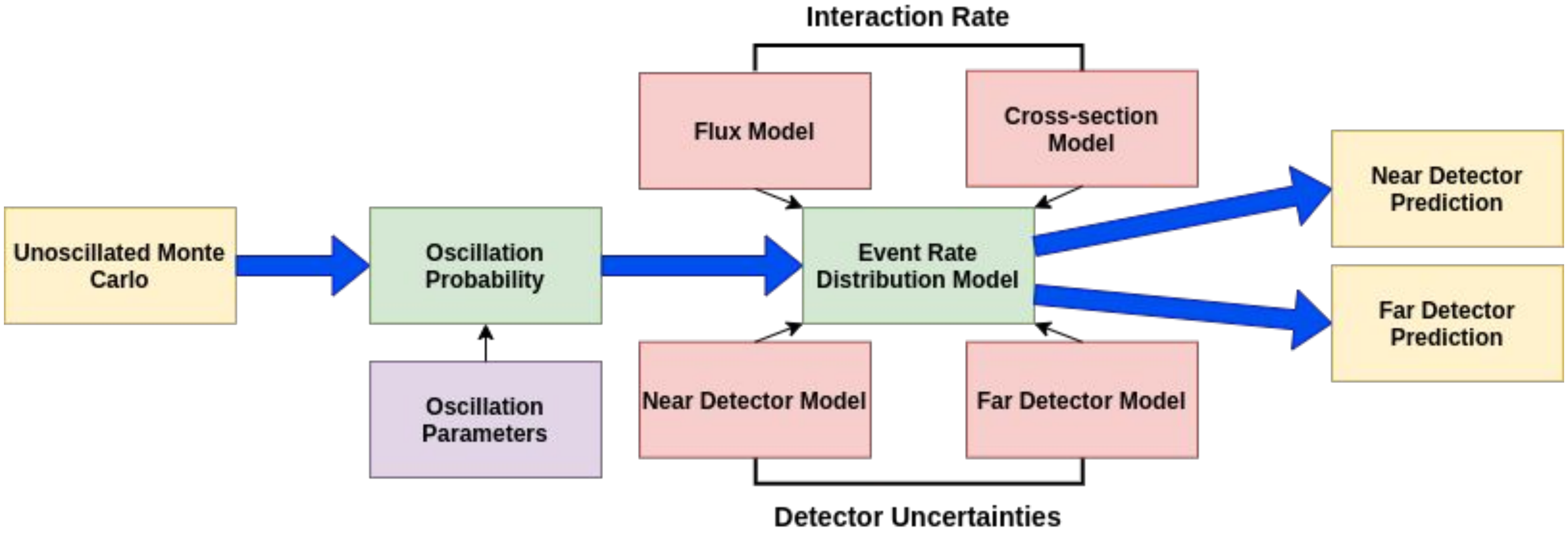


[See Meghna Bhattacharya's talk!]

Science and Technology Facilities Council

Analysis Strategy

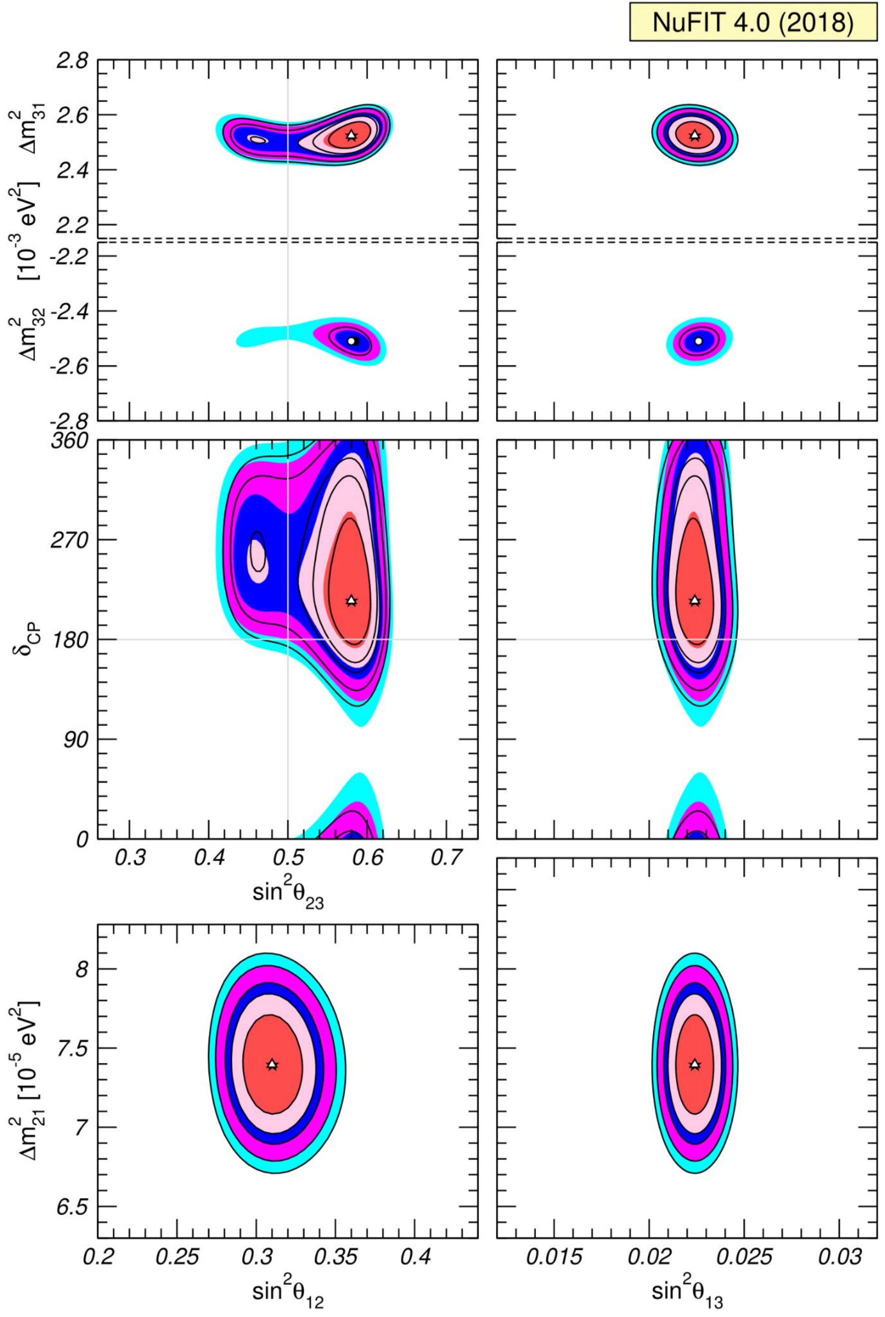
- **Oscillation** probabilities, **flux** model, **interaction** model and **detector** model → **predictions** of **far and near detector spectra**
- Build **likelihood space** as a function of **oscillation** and **systematic** parameters
- **MCMC** to explore the full likelihood space
- **Bayesian inference** of oscillation parameters and systematic parameters



Science and Technology Facilities Council

Sensitivity Study Details

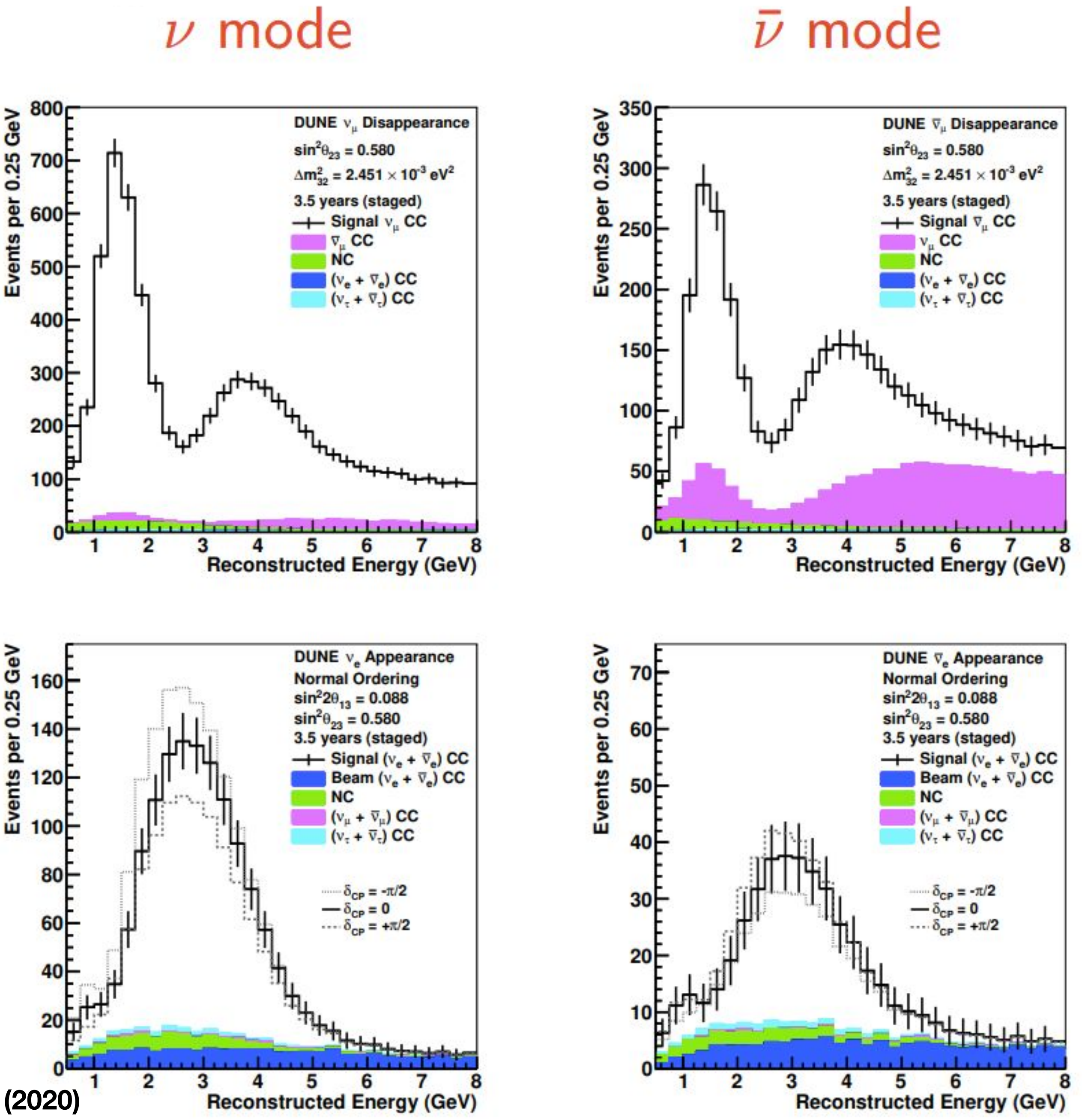
- **Simultaneous** fit to FD and ND samples
- **NuFit 4.0 normal ordering (NO)** parameter values chosen:
  - **Flat priors** in oscillation parameters **of interest**
  - Gaussian solar constraint used for $\sin^2(\theta_{12})$ and Δm_{21}^2 from NuFit 4.0
- Markov chain ran for **180 million** steps
  - Sufficient for reliable **3σ intervals**
- Systematic model: **(288 pars)** for **xsec (55 pars)**, **flux (204 pars)** and **detector (24 pars)**
- Using **nominal staged 7 year exposure (336 ktMWyr)**



Science and Technology Facilities Council

Samples

- 4 FD samples: **$\nu/\bar{\nu}$** and **numu-like/nue-like**
    - +2 ND samples: **$\nu/\bar{\nu}$ CC numu inclusive**
- **$\sin^2(2\theta_{23})$** sensitivity from dip in disappearance spectra
    - **Δm^2_{32}** sensitivity from position of dip
- **$\sin^2(\theta_{23})$** and **$\sin^2(\theta_{13})$** sensitivity from appearance
    - Allows for **θ_{23} octant selection**
- **δ_{CP}** from **ν vs $\bar{\nu}$** + appearance rate/shape



Eur. Phys. J. C 80, 978 (2020)

Science and Technology Facilities Council

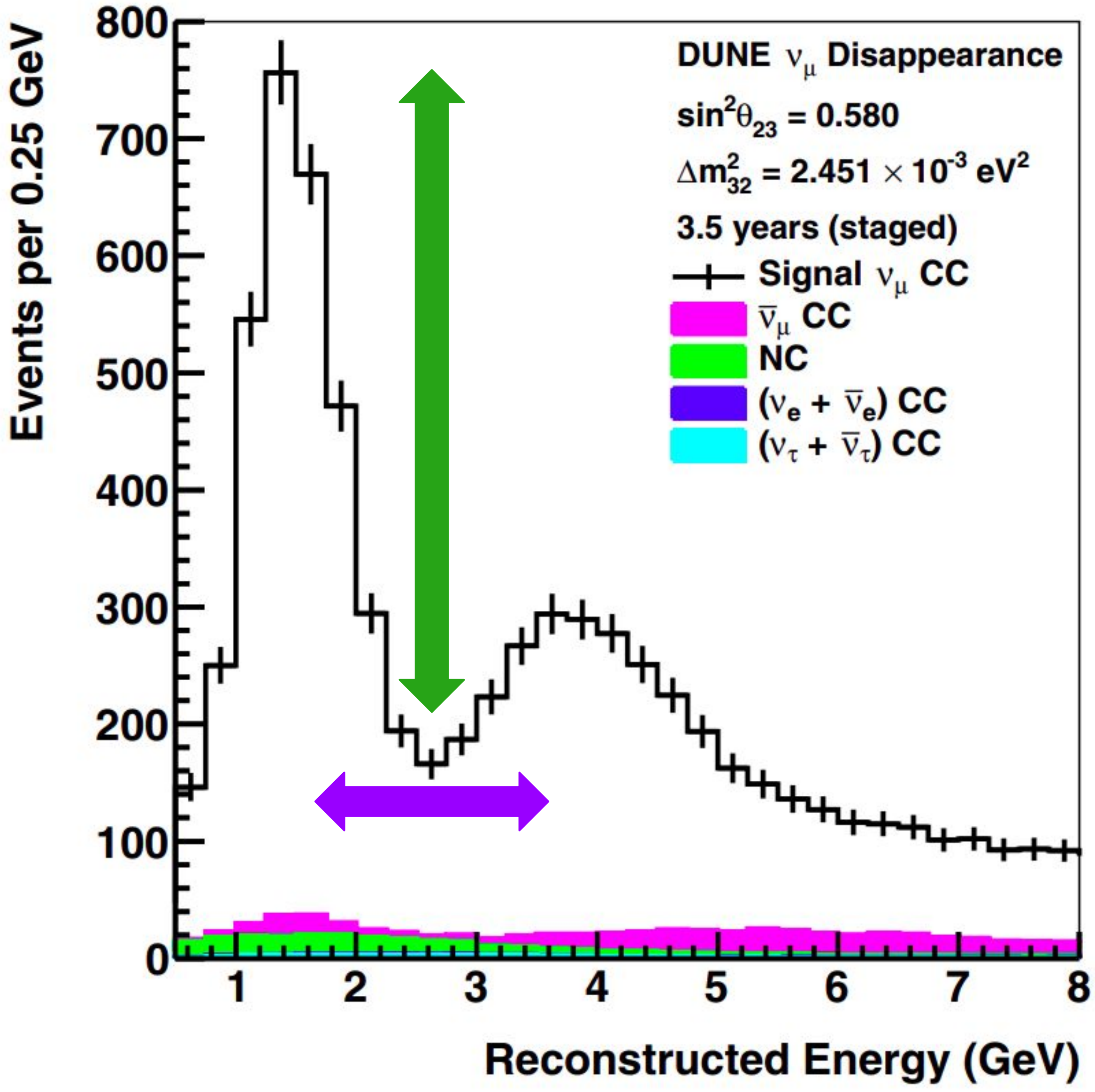
Samples

- 4 FD samples: $\nu/\bar{\nu}$ and **numu-like/nue-like**
  - +2 ND samples: **$\nu/\bar{\nu}$ CC numu inclusive**

- **$\sin^2(2\theta_{23})$** sensitivity from dip in disappearance spectra
  - **Δm_{32}^2** sensitivity from position of dip

- **$\sin^2(\theta_{23})$** and **$\sin^2(\theta_{13})$** sensitivity from appearance
  - Allows for **θ_{23} octant selection**

- **δ_{CP}** from **ν vs $\bar{\nu}$** + appearance rate/shape



Eur. Phys. J. C 80, 978 (2020)

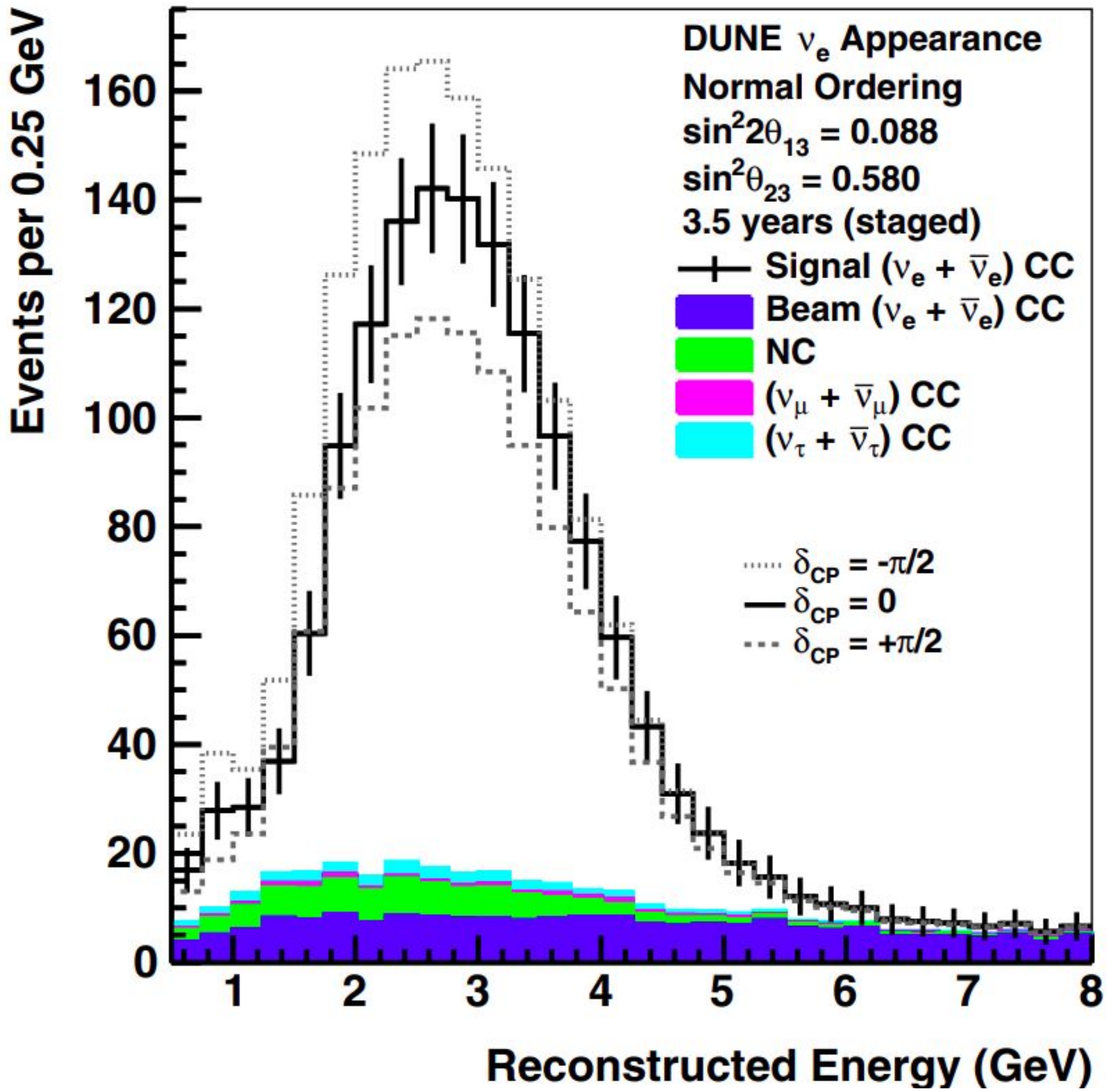
Samples

- 4 FD samples: **$\nu/\bar{\nu}$** and **numu-like/nue-like**
  - +2 ND samples: **$\nu/\bar{\nu}$ CC numu inclusive**

- **$\sin^2(2\theta_{23})$** sensitivity from dip in disappearance spectra
  - **Δm^2_{32}** sensitivity from position of dip

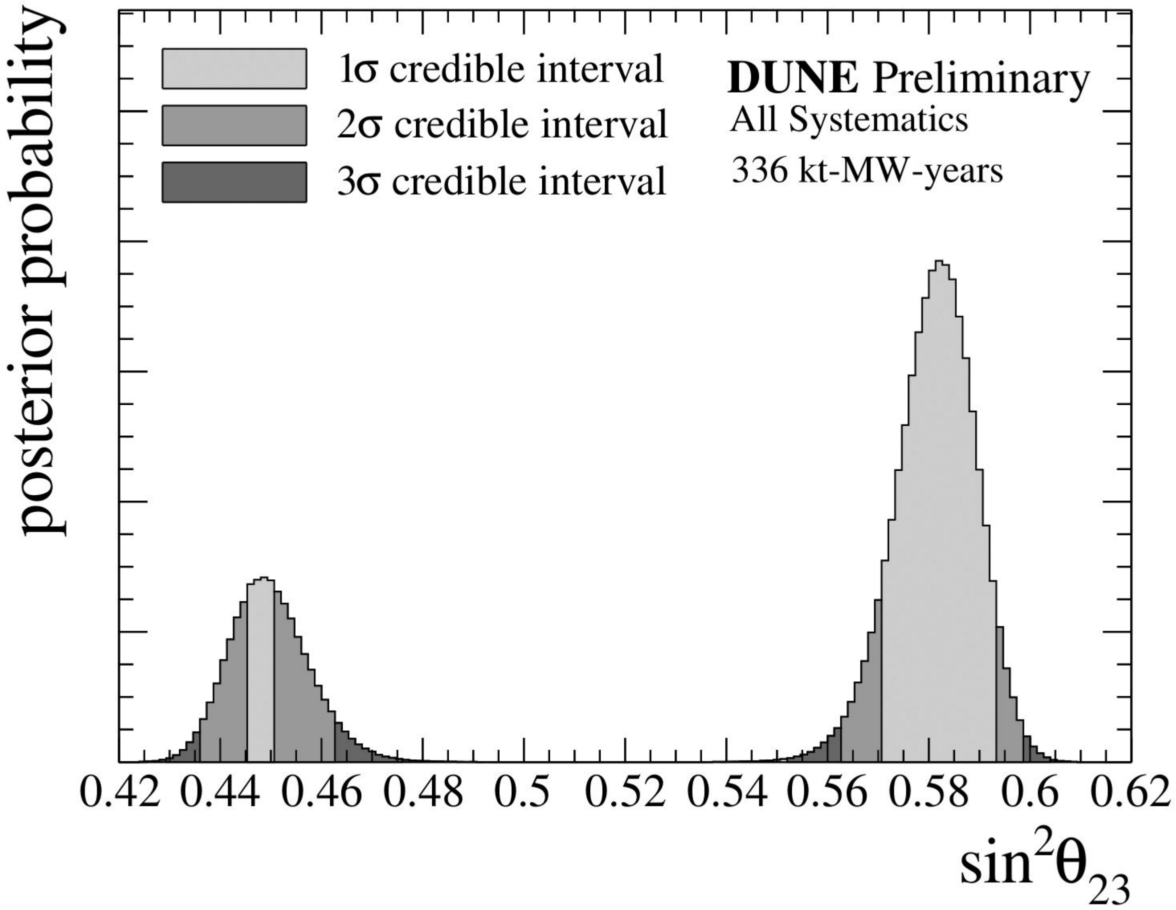
- **$\sin^2(\theta_{23})$** and **$\sin^2(\theta_{13})$** sensitivity from appearance
  - Allows for **θ_{23} octant selection**

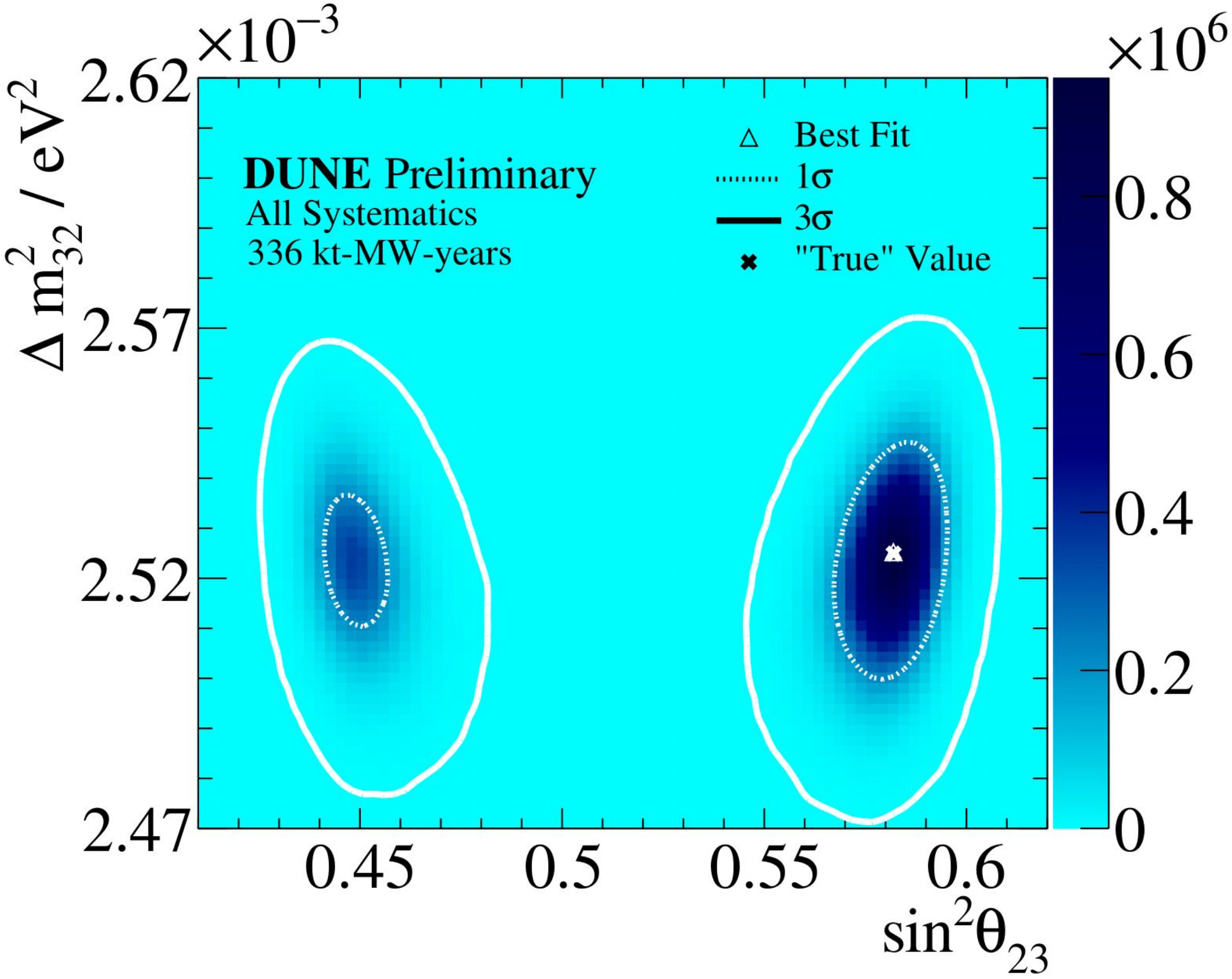
- **δ_{CP}** from **ν vs $\bar{\nu}$** + appearance rate/shape



Eur. Phys. J. C 80, 978 (2020)

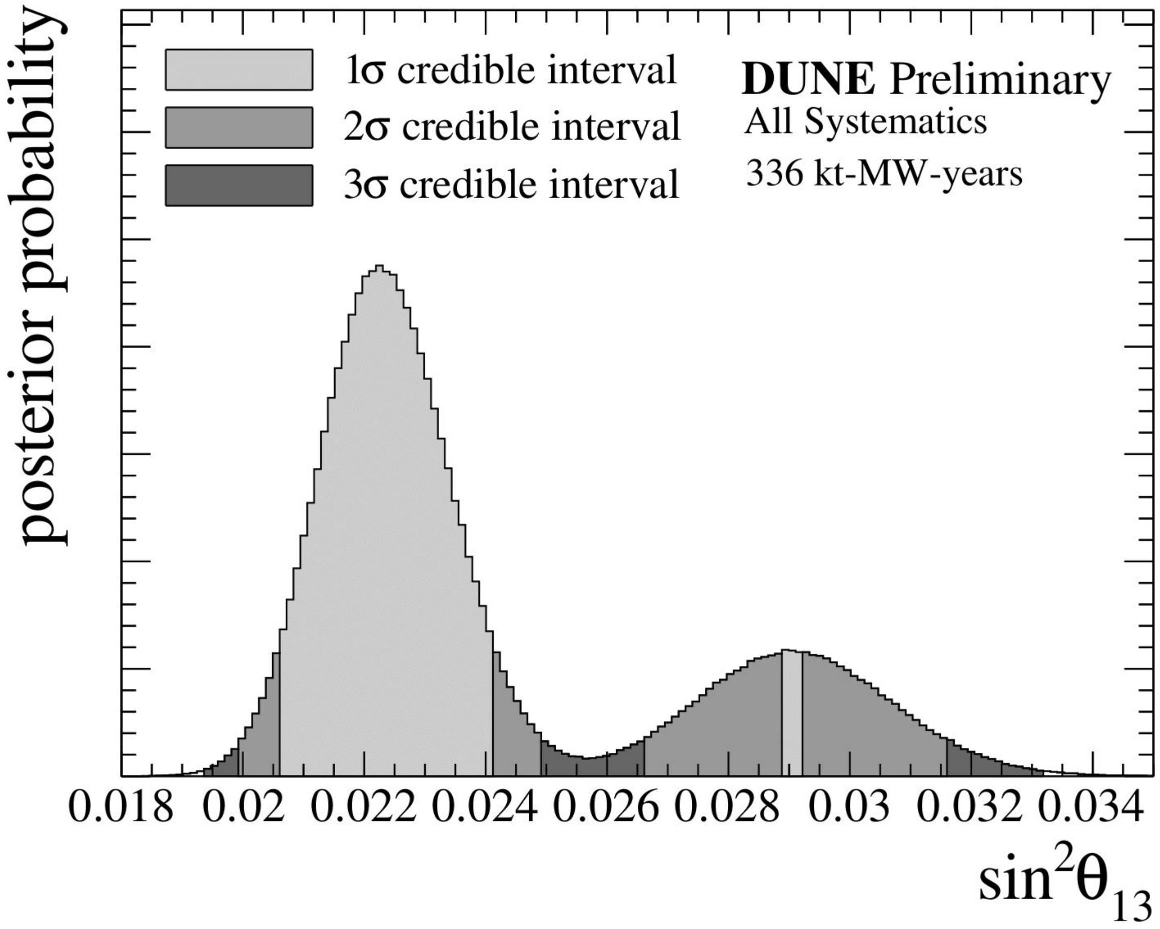
θ_{23} Sensitivity

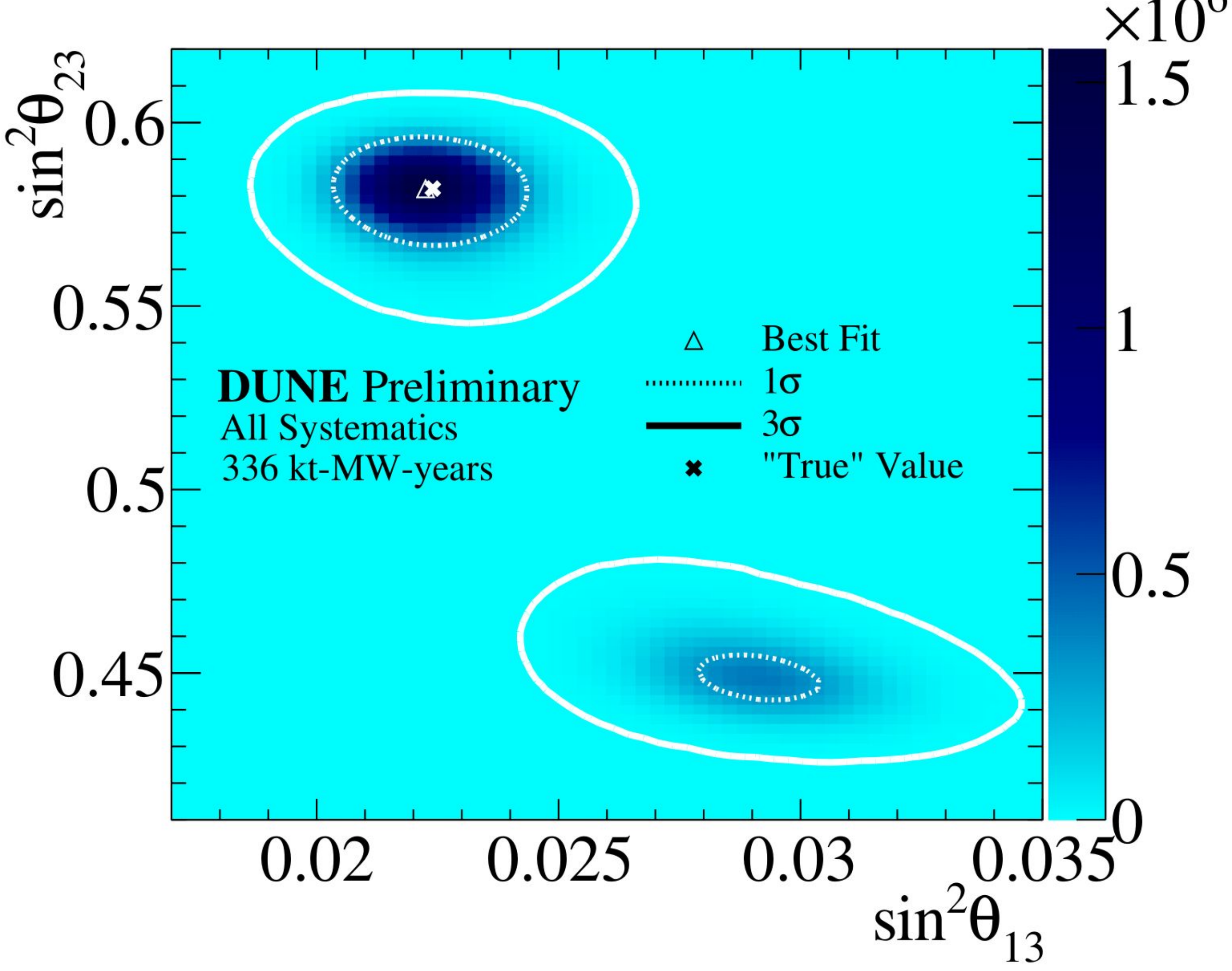




- Both θ_{23} octants being evaluated → **correct octant chosen**
- **No posterior in IO**

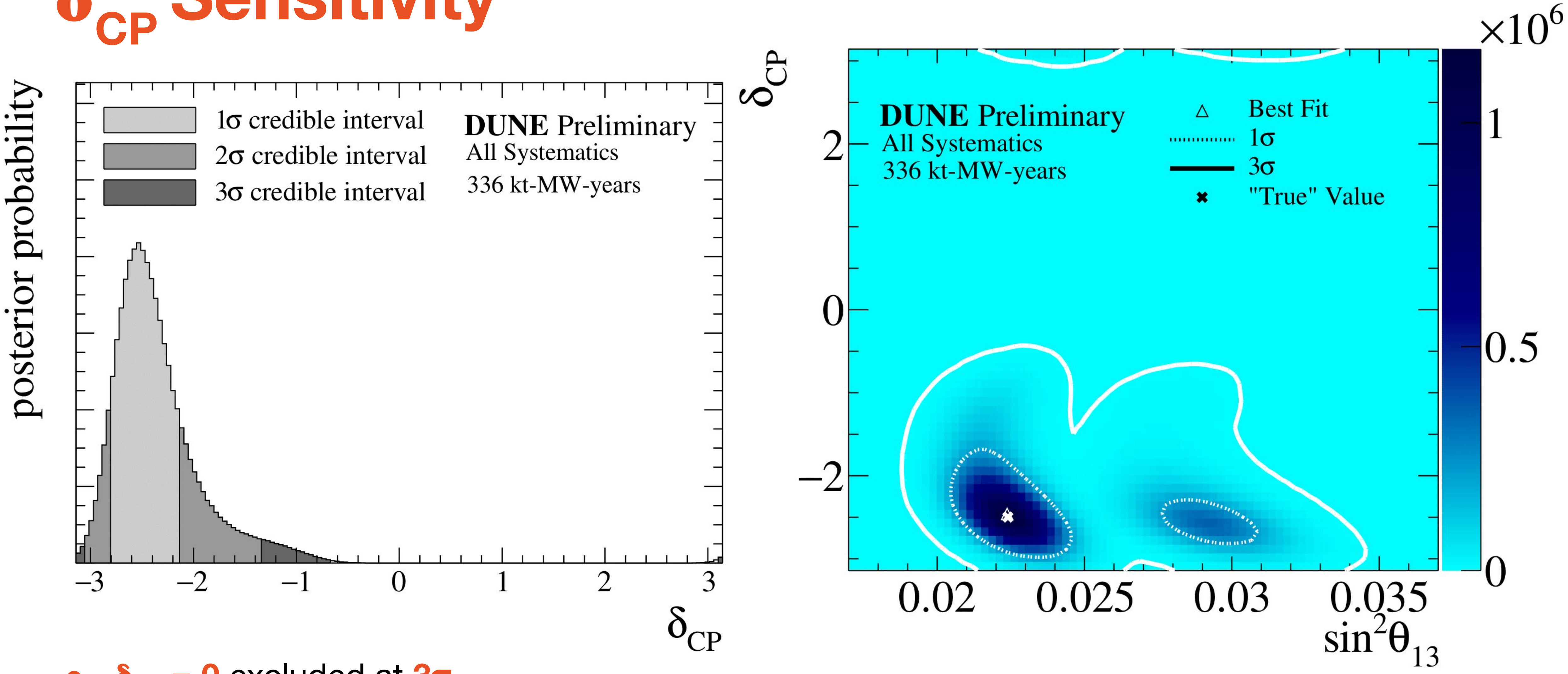
θ_{13} Sensitivity





- Second peak
- Some degeneracy in θ_{13} → as a result of θ_{23} octant degeneracy

δ_{CP} Sensitivity



- $\delta_{CP} = 0$ excluded at 3σ
- Tail towards 0 caused by δ_{CP} octant degeneracy → mostly sensitive to $\sin\delta_{CP}$

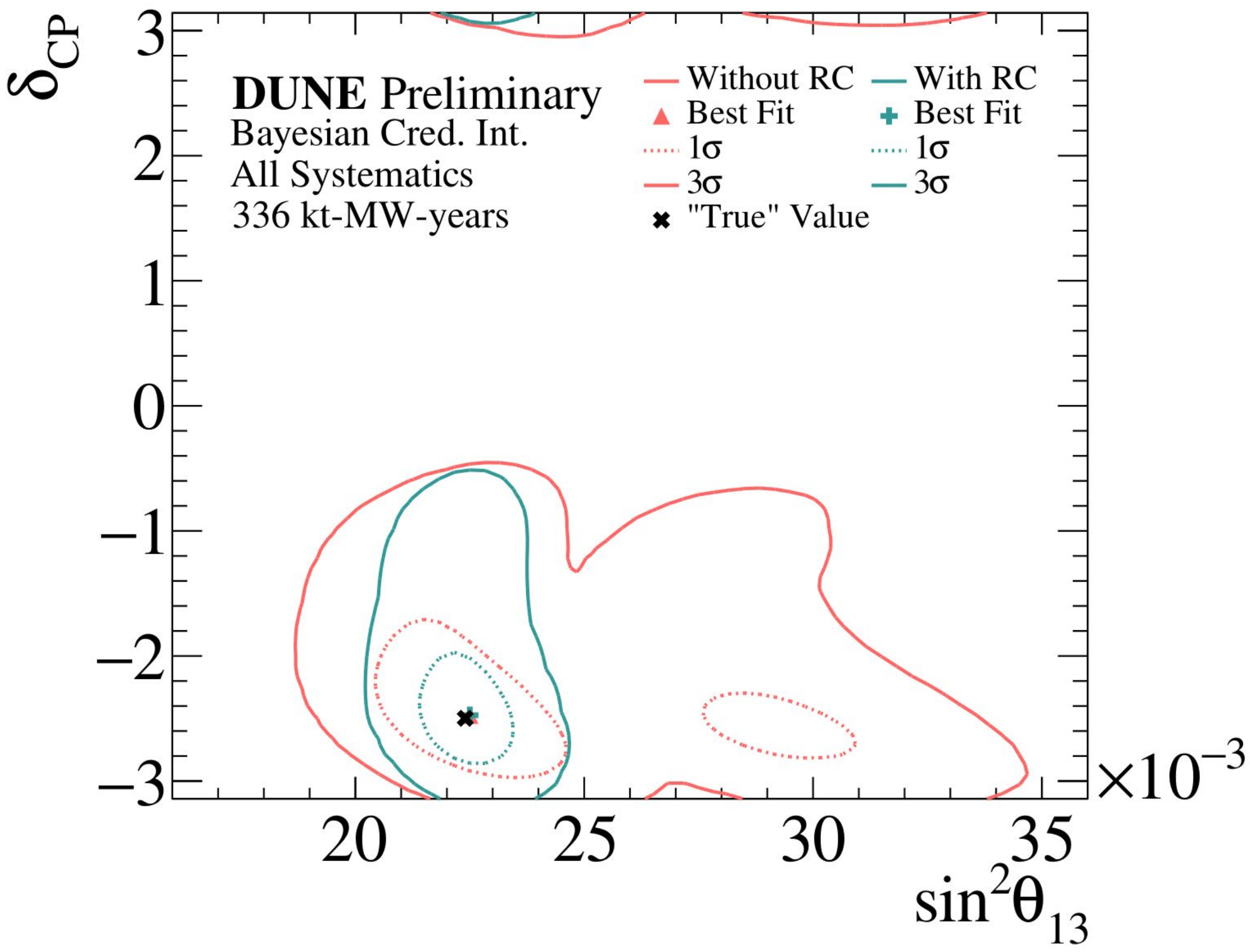
MCMC Prior Reweighting and Reprojection

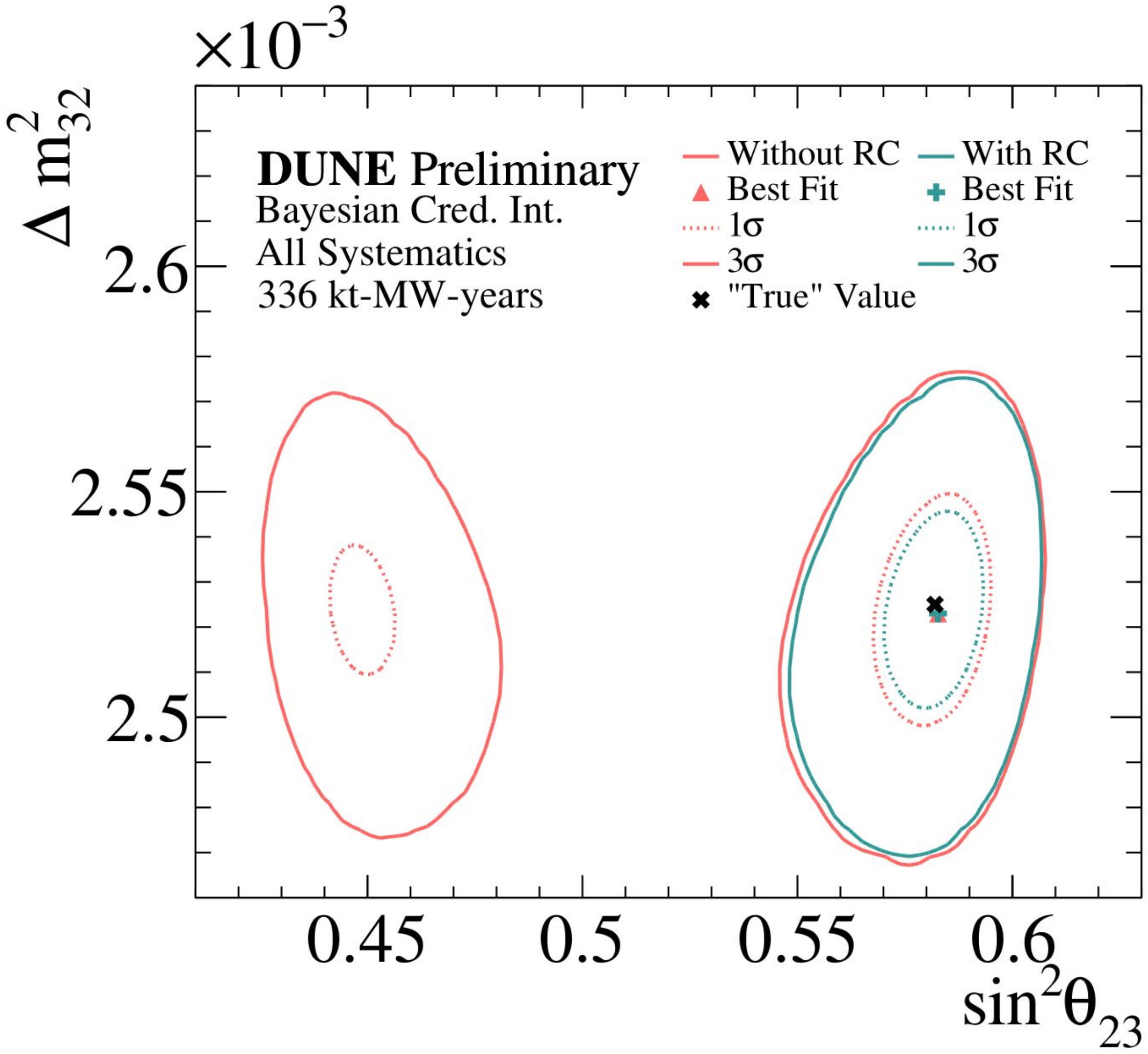
- MCMC allows the ability to **reweight the posterior distribution given a change of prior**
  - I.e. flat $\sin^2(\theta_{13})$ → reactor constraint

- One caveat is that there are **enough MCMC steps** in the region that the new posterior favours

- Also **trivial** to produce a posterior distribution in some **new variable** that is a function of the variables included in the MCMC
  - I.e. if you have a posterior for **α** and **β** → easy to produce any distribution of **f(α, β)**

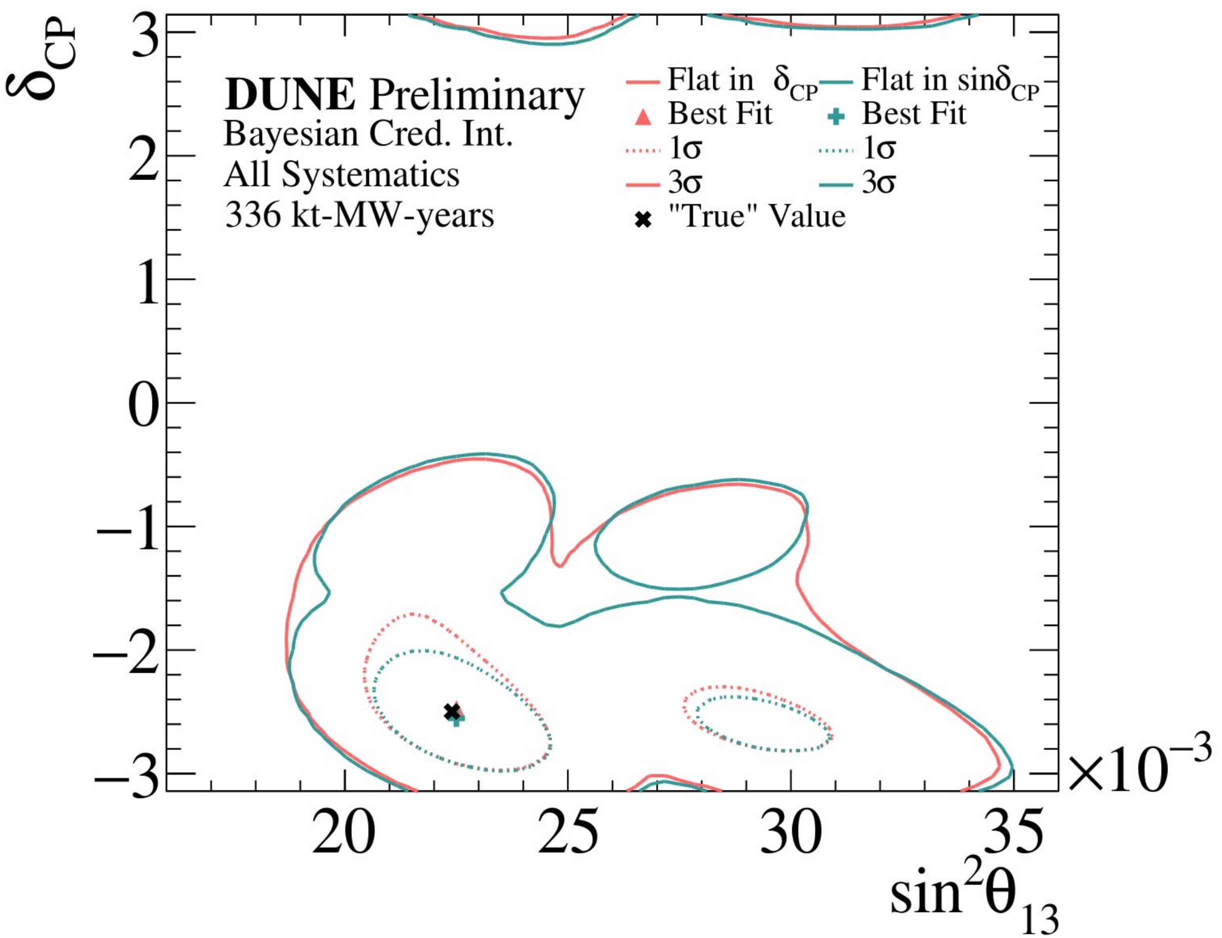
Reactor Constraint

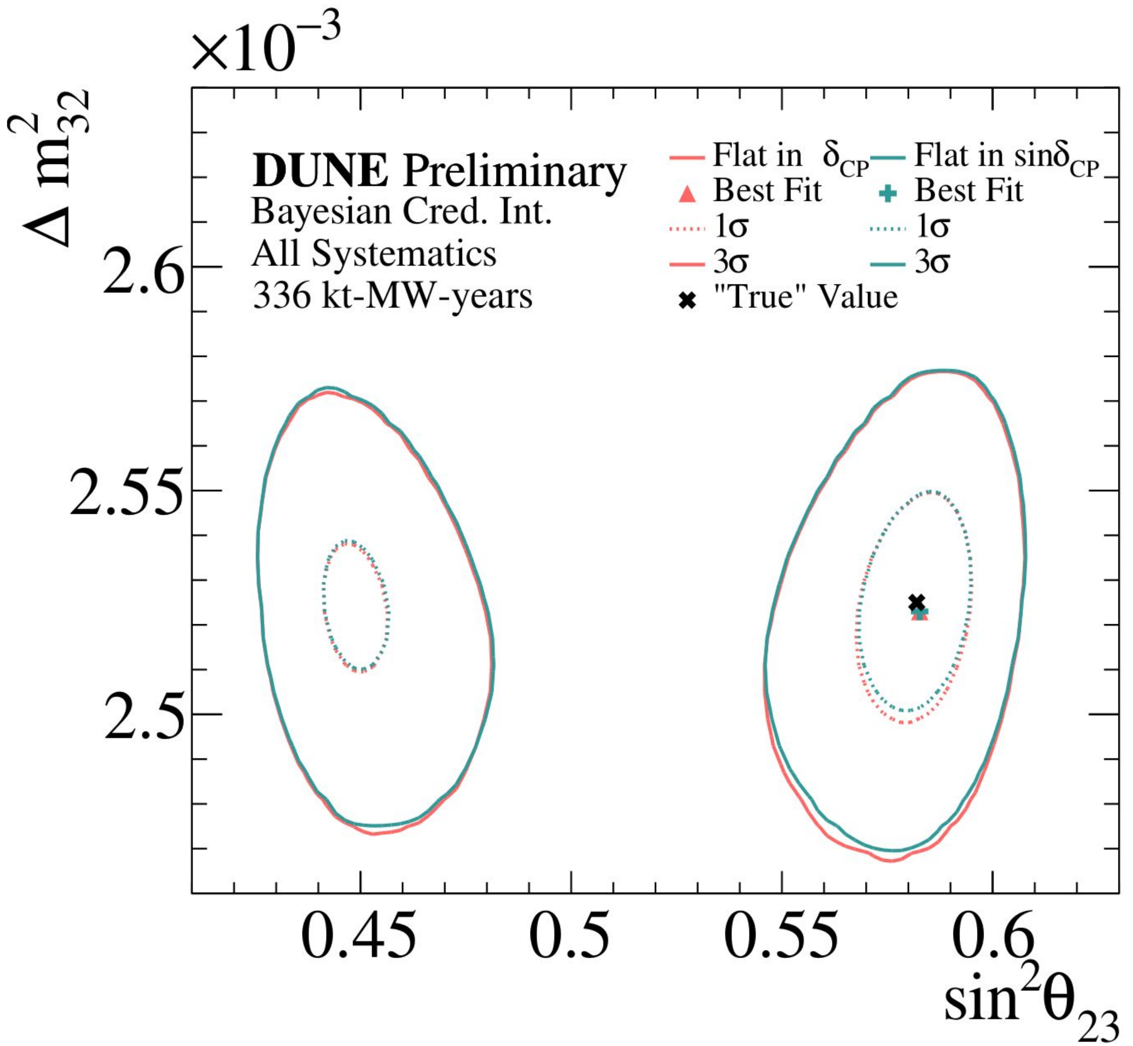




- Second θ_{13} peak completely suppressed
- Wrong θ_{23} octant also suppressed

δ_{CP} Prior Change



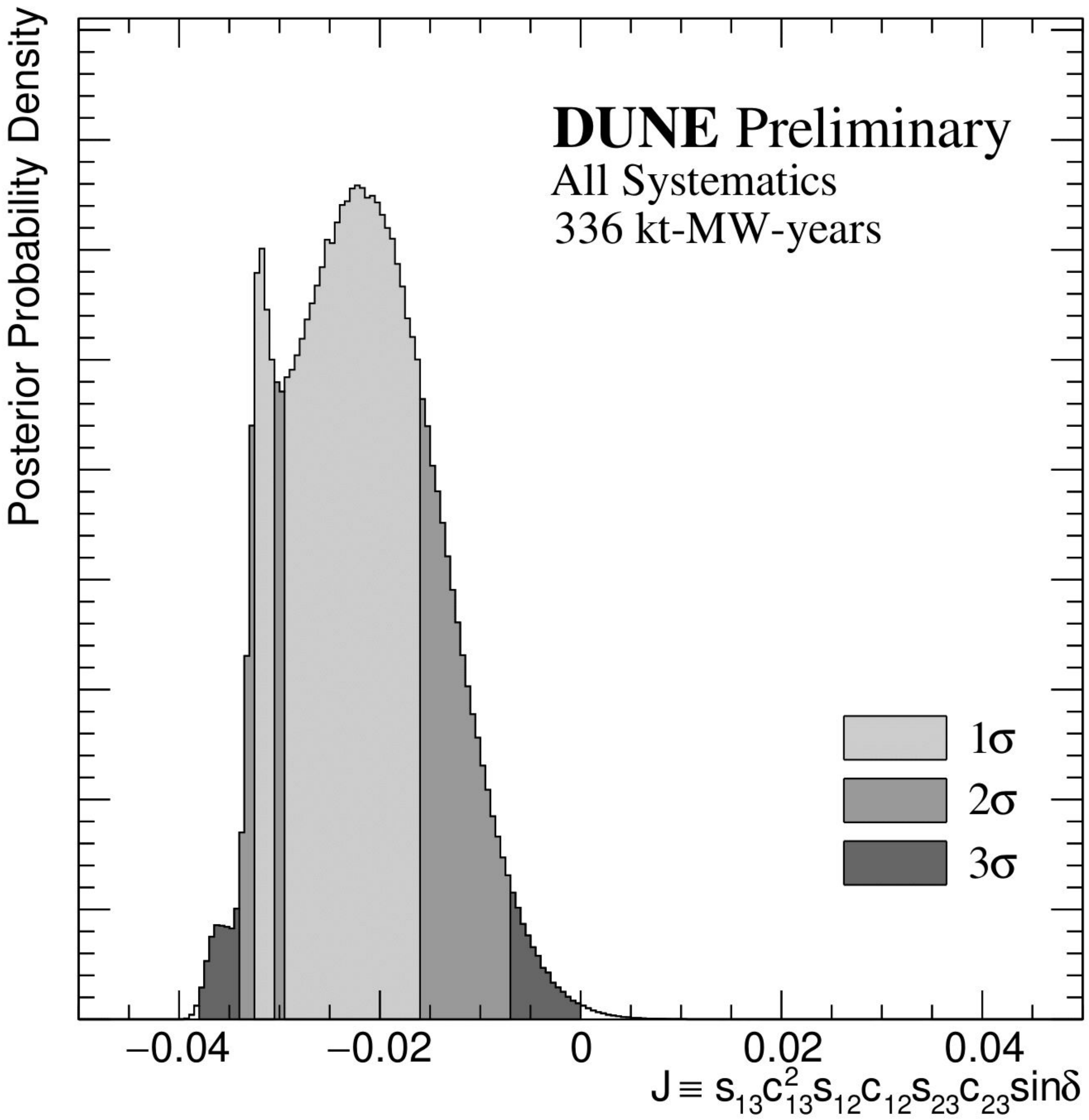


- Flat prior in δ_{CP} results in **non-uniform prior** in other quantities e.g. **$\sin\delta_{CP}$** or **$\cos\delta_{CP}$**
- Flat **$\sin\delta_{CP}$** prior of interest → **CPV is a function of $\sin\delta_{CP}$**

Jarlskog Invariant

- The **Jarlskog invariant (J_{CP})** indicates the magnitude of **CP violation**
  - Value of 0 indicates **no CP violation**

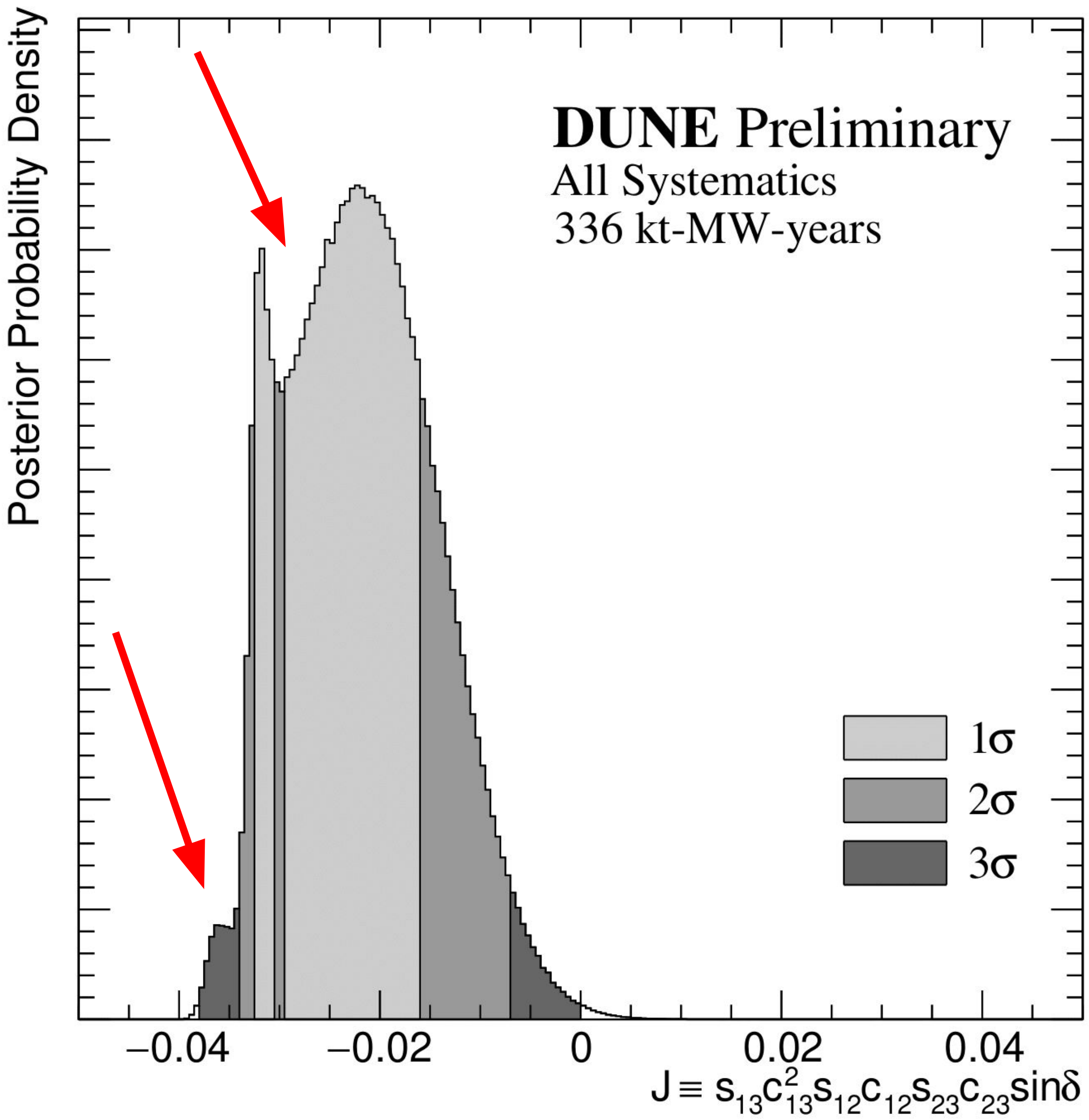
$$J_{CP} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})\sin\delta_{CP}$$



Jarlskog Invariant

- The **Jarlskog invariant (J_{CP})** indicates the magnitude of **CP violation**
  - Value of 0 indicates **no CP violation**

- **Two features** in the distribution



$$J_{CP} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})\sin\delta_{CP}$$

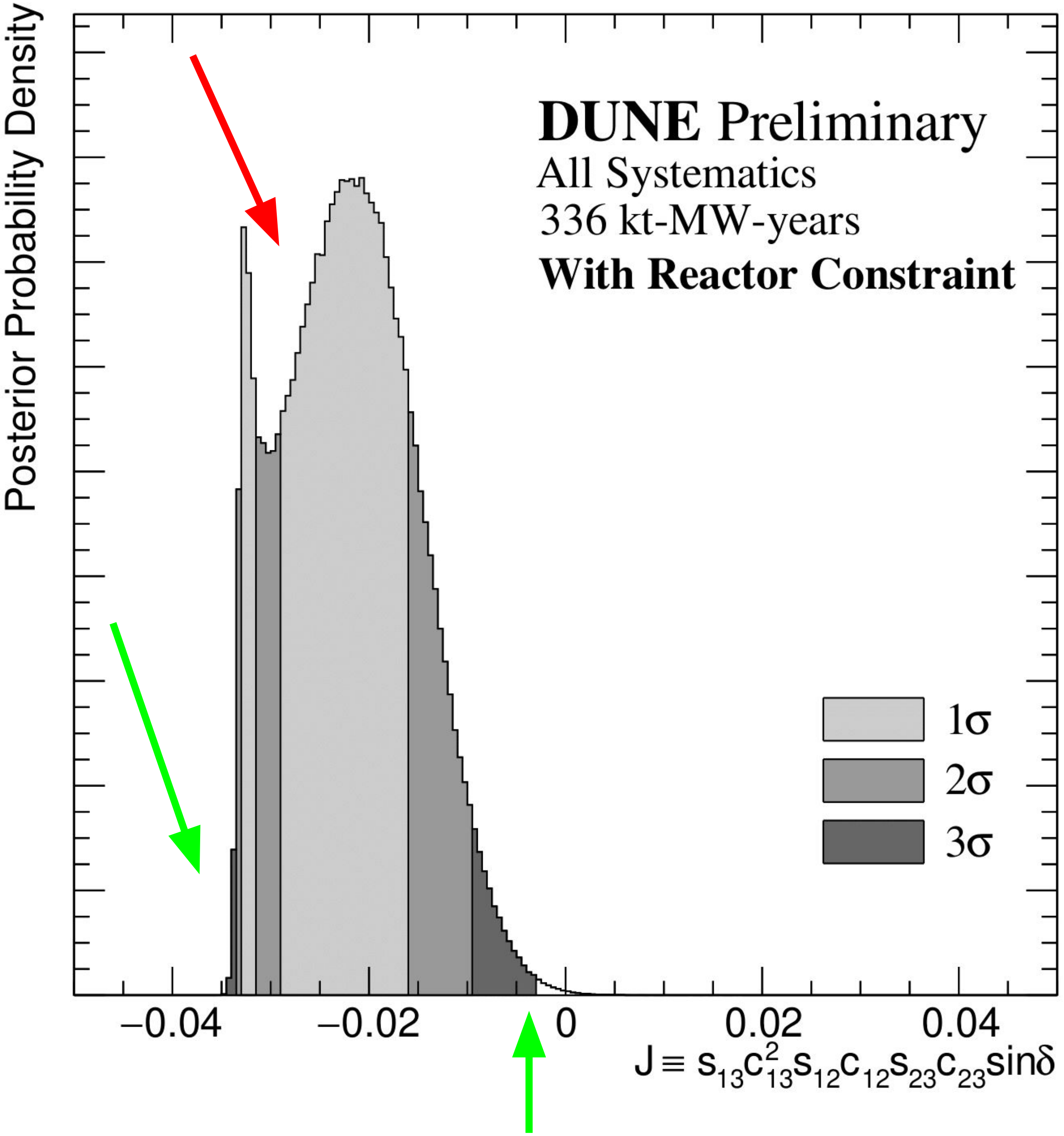
Jarlskog Invariant

- The **Jarlskog invariant (J_{CP})** indicates the magnitude of **CP violation**
  - Value of 0 indicates **no CP violation**

- **Two features** in the distribution

- With **reactor constraint**:
  - **J_{CP} = 0 excluded at 3σ**
  - Removes **outer bump**

$$J_{CP} = \frac{1}{8} \cos\theta_{13} \sin(2\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{23}) \sin\delta_{CP}$$



Science and Technology Facilities Council

Jarlskog Invariant

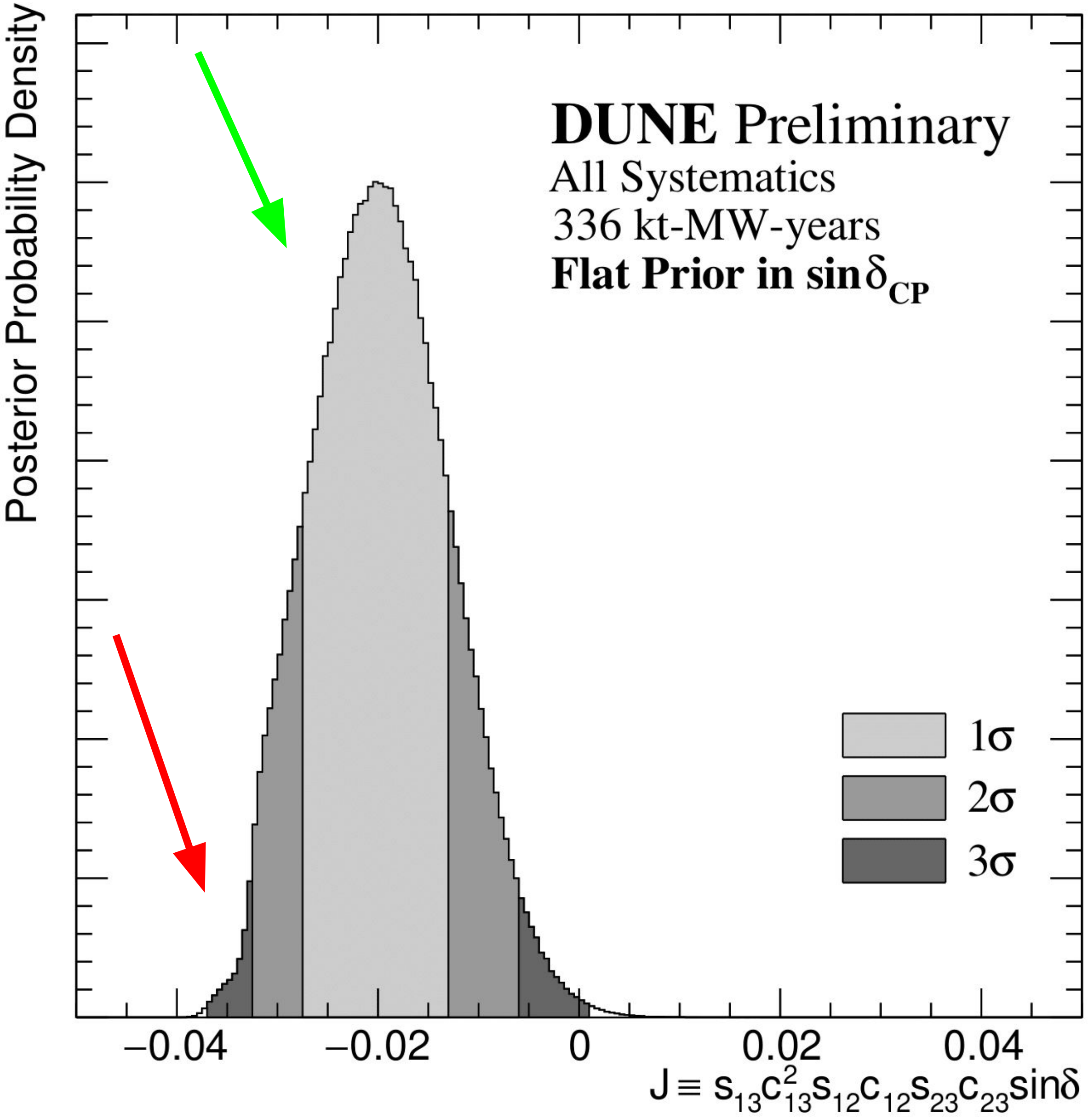
- The **Jarlskog invariant (J_{CP})** indicates the magnitude of **CP violation**
  - Value of 0 indicates **no CP violation**

- **Two features** in the distribution

- With **reactor constraint**:
  - $J_{CP} = 0$ **excluded at 3σ**
  - Removes **outer bump**

- **Flat $\sin\delta_{CP}$ prior:**
  - Removes **dip around peak**

$$J_{CP} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})\sin\delta_{CP}$$



Summary

- DUNE will enable **an exciting physics program** and aims to make **precise measurements** of the oscillation parameters:
  - Definitively measure the **MO** regardless of other oscillation parameters
  - Sensitivity to **CPV** and **θ_{23} octant**

- **First Bayesian analysis of DUNE** has been performed
  - Complementary to existing and future frequentist sensitivities

Science and Technology Facilities Council

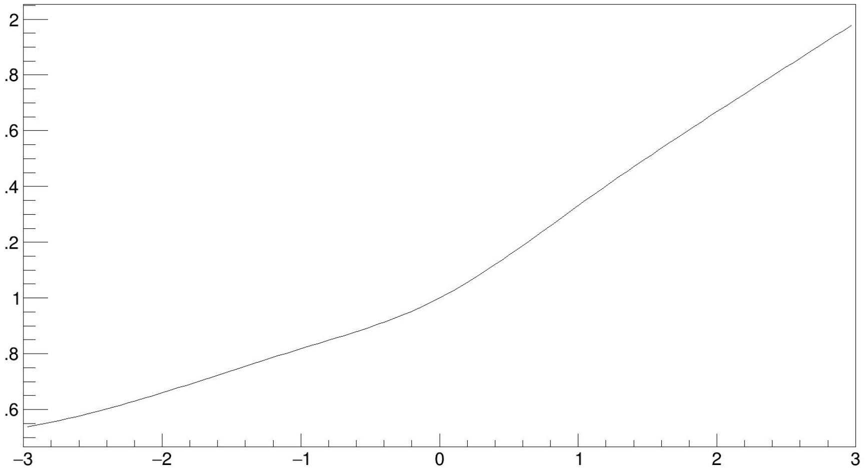
Back up

Science and Technology Facilities Council

Systematic Implementation

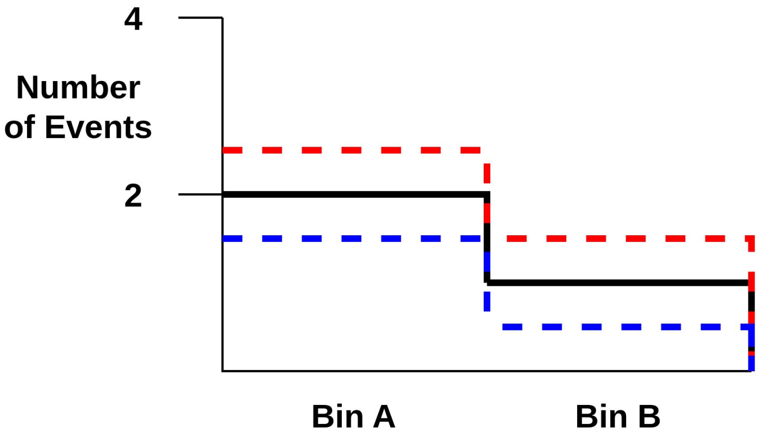
- **High statistics** in next-generation near detectors requires **sophisticated** systematic implementation
- We need to model a complex/degenerate likelihood space -> **different types of systematics:**

Splines



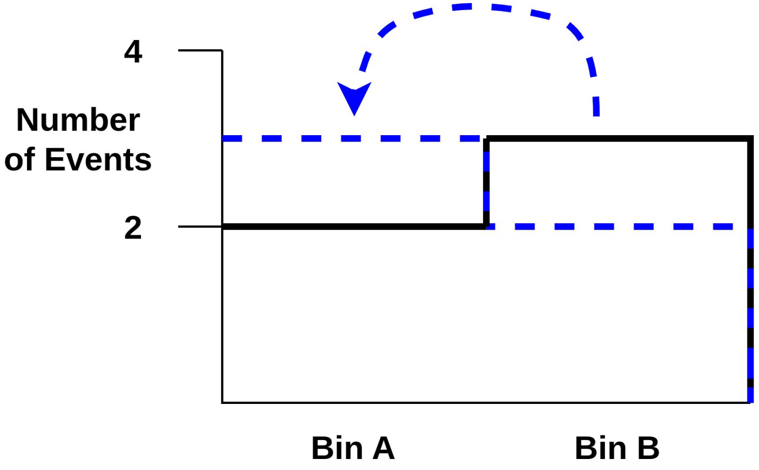
- Continuous response functions using piecewise cubic interpolation
- Binned or **event-by-event**
- Cross-section parameters

Normalisation



- Weights events up and down relative to parameter movement
- Apply to specific kinematic ranges and events
- Flux parameters

Shift-like



- Move events from one bin to another
- Systematics which **change reconstructed variables**
- Generally for detector systematics

UKRI Science and Technology Facilities Council DUNE

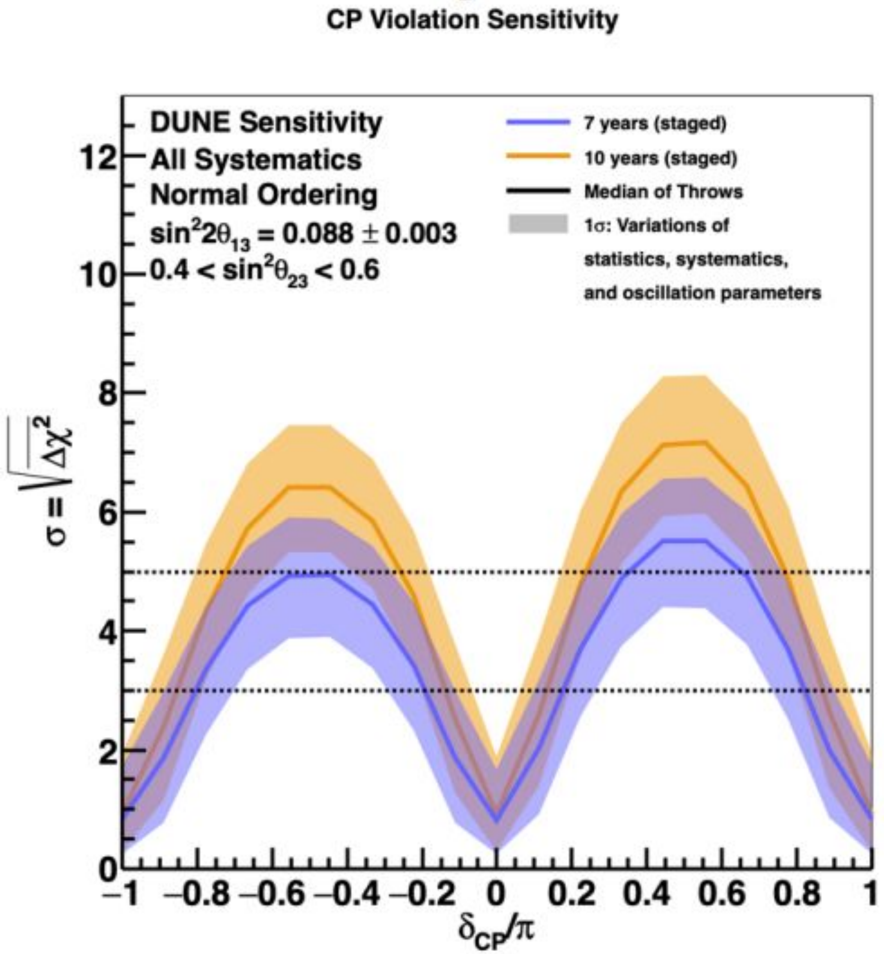
NuFit 4.0 Parameters

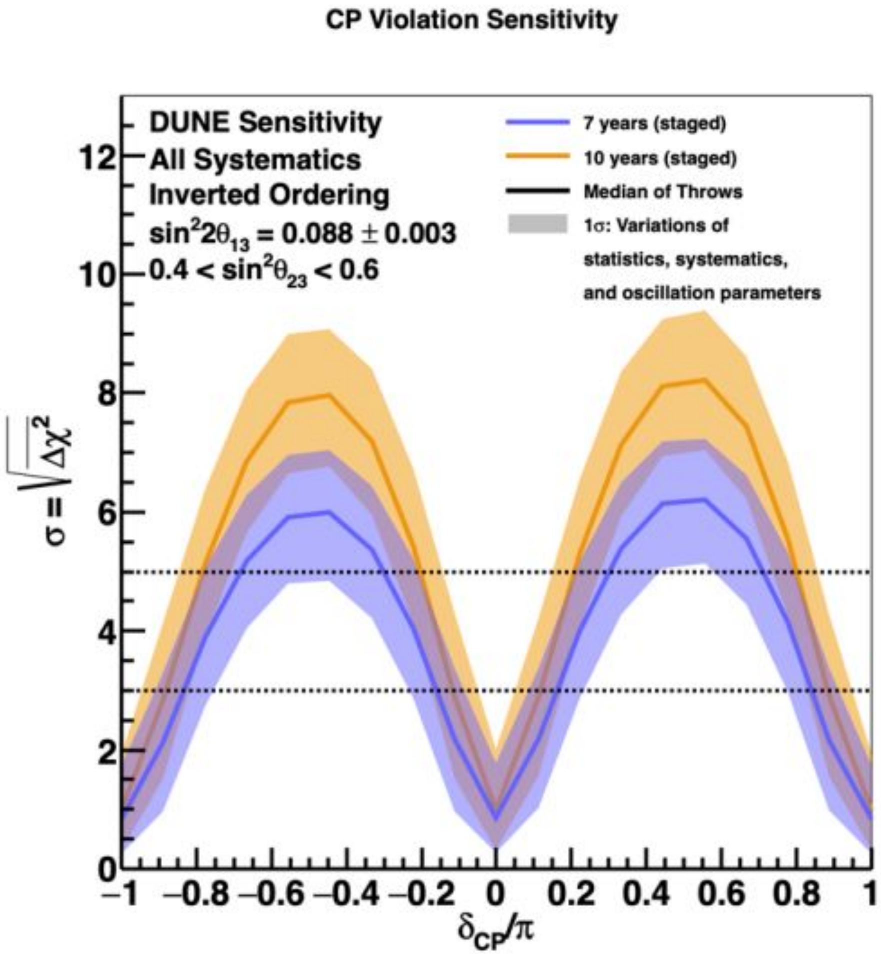
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{\mathrm{CP}}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

- NuFIT 4.0 (2018), www.nu-fit.org, JHEP 01 (2019) 106 – arXiv:1811.05487

UKRI Science and Technology Facilities Council DUNE

CPV Sensitivity

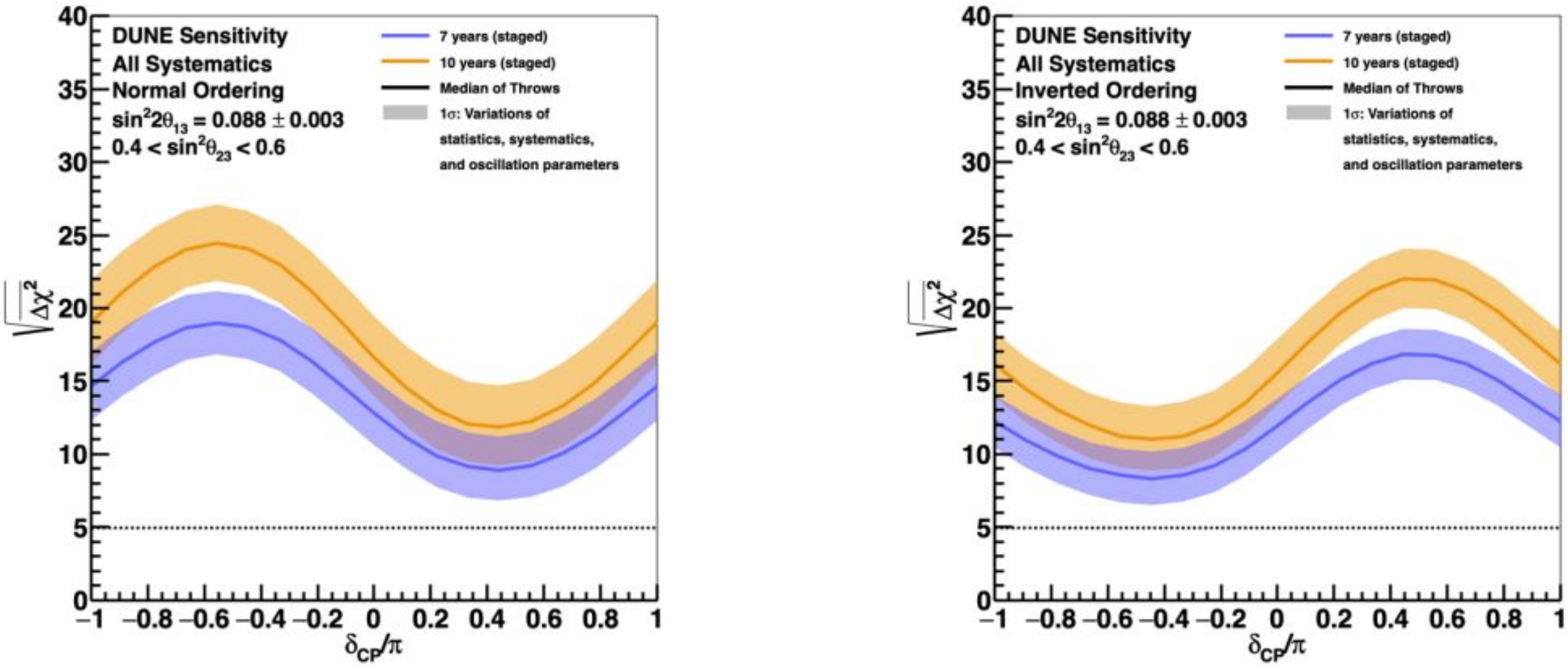




- After 10 years (staged), there is significant CP violation (**$\delta_{CP} \neq 0, \pi$**) discovery potential across true values of **δ_{CP}** and for both hierarchies

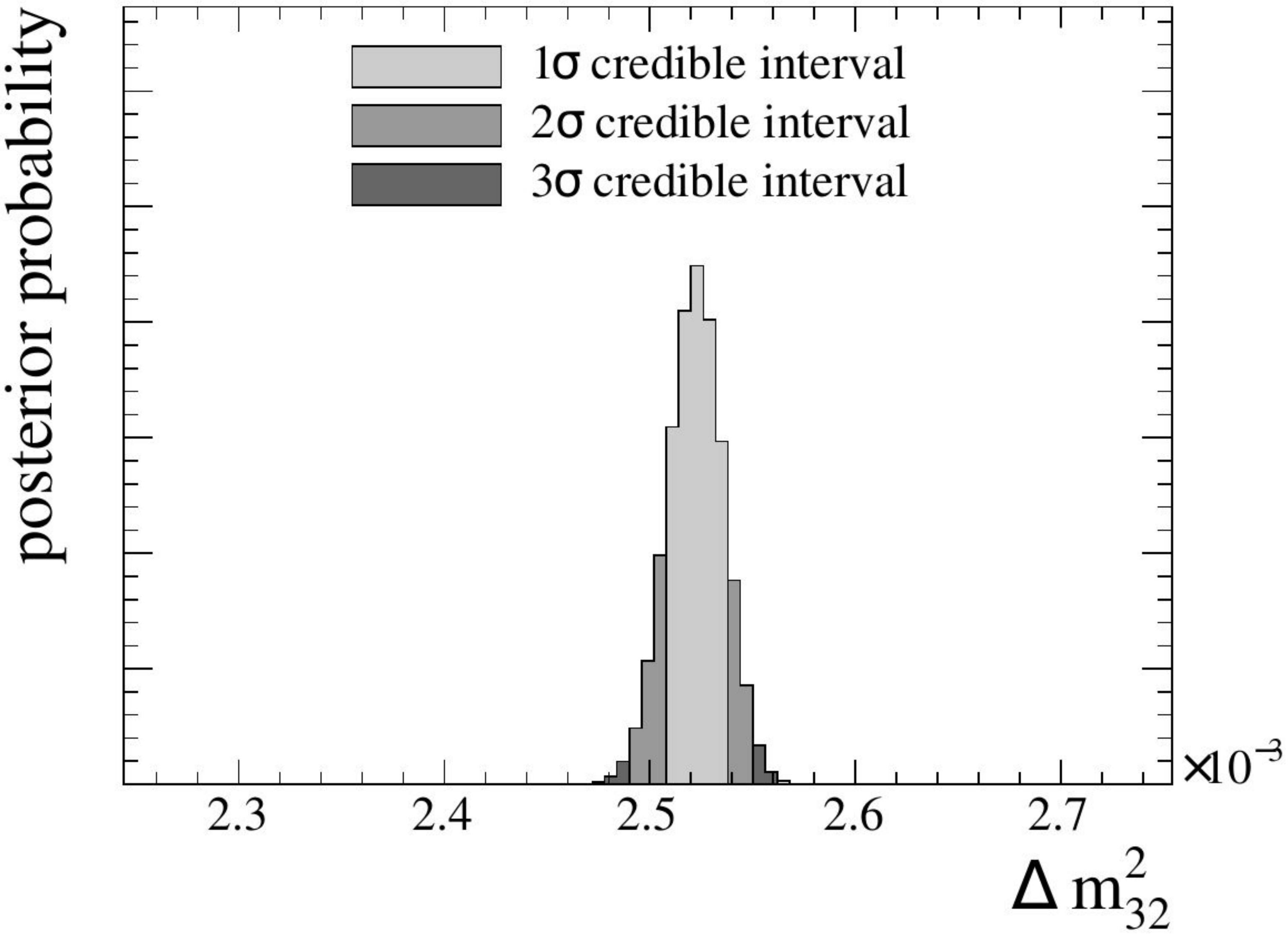
Science and Technology Facilities Council

Mass Ordering Sensitivity



- Obtain a definitive answer for the mass hierarchy within 7 years (staged), regardless of the values of the other oscillation parameters

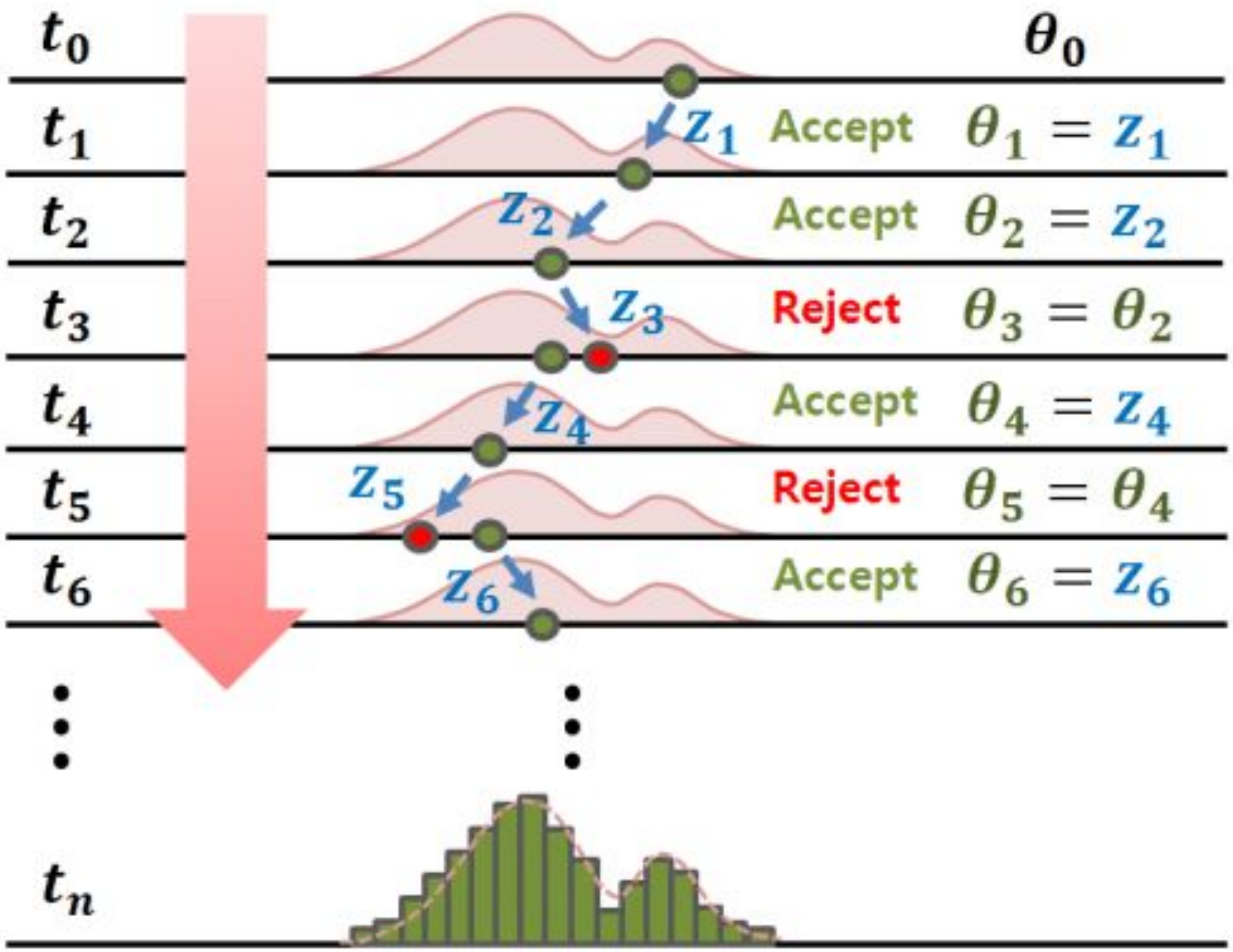
Δm_{32}^2 Sensitivity



Science and Technology Facilities Council

MCMC - Markov Chain Monte Carlo

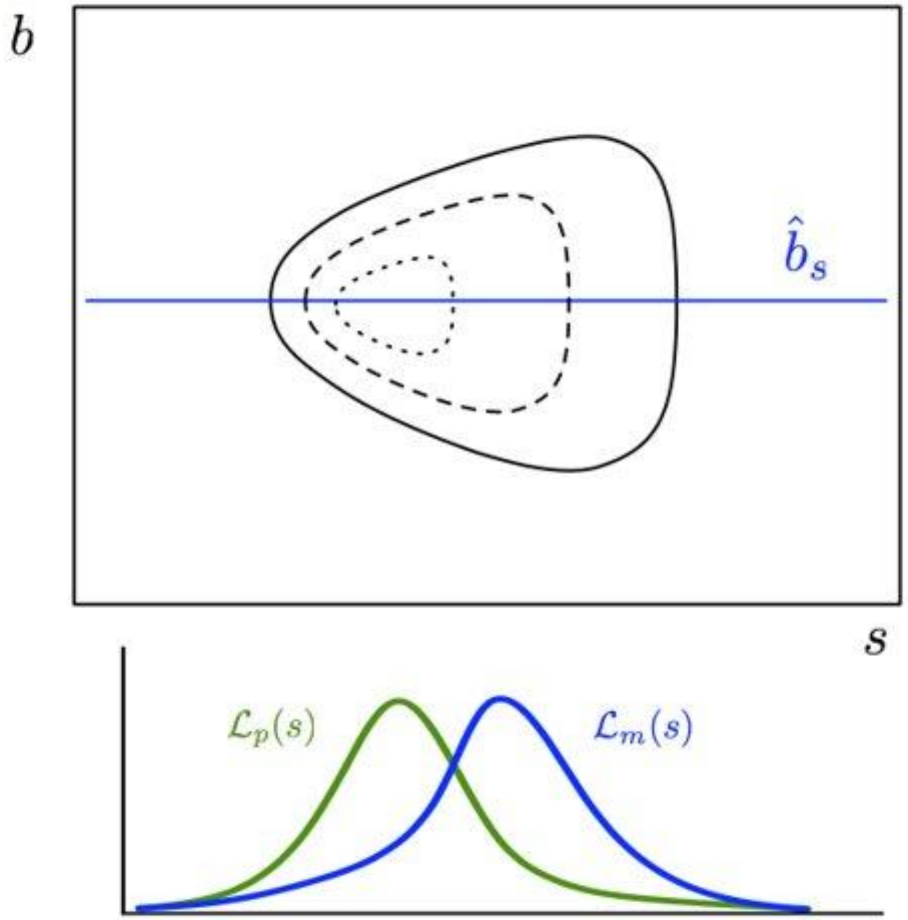
- Semi-random walk around the **full** parameter space
- Metropolis-Hastings algorithm for **accepting** or **rejecting** steps
- Builds up distribution of steps in each parameter -> **proportional to target distribution**
- Scales well with dimensions
- Can deal with **discontinuous likelihoods** (caused by event shifting)



Science and Technology Facilities Council

Bayesian Inference

- MCMC let's evaluate a nearly impossible integral to get the **posterior distribution**
- Multi-dimensional posterior… we only want oscillation parameters
- **Marginalisation** - integrate out nuisance parameters
- MCMC gives us this integral for **free**



Bayes' theorem:

$$P(A \mid B) = \frac{P(B \mid A) \cdot P(A)}{P(B)}$$