DUNE Oscillation Physics: Bayesian Sensitivity Studies

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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 .

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

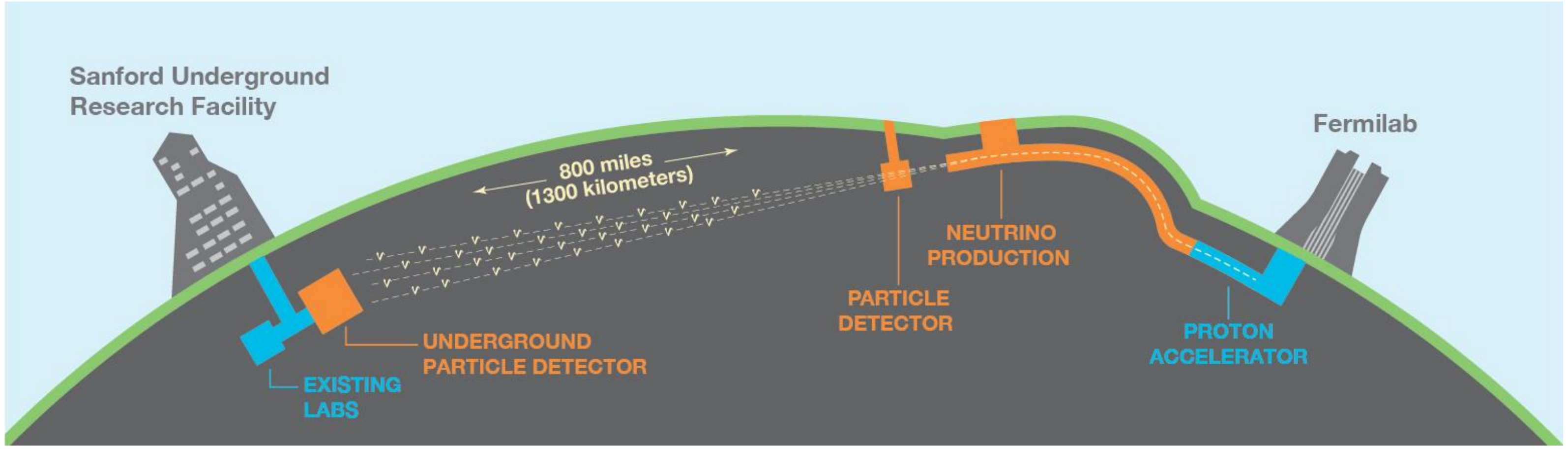
DUNE Collaboration

The DUNE experiment is a large international collaboration with > 1400 collaborators from > 200 institutions in 30 countries

DUNE collaboration meeting January 2023

Deep Underground Neutrino Experiment

- DUNE will make a beam of either ν_μ or $\nu_\mu$bar 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



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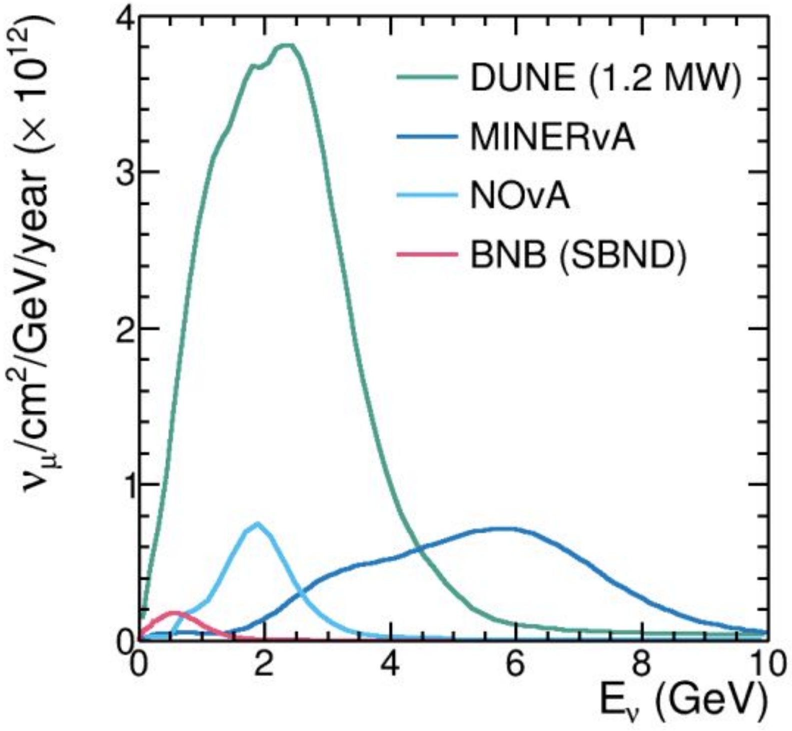
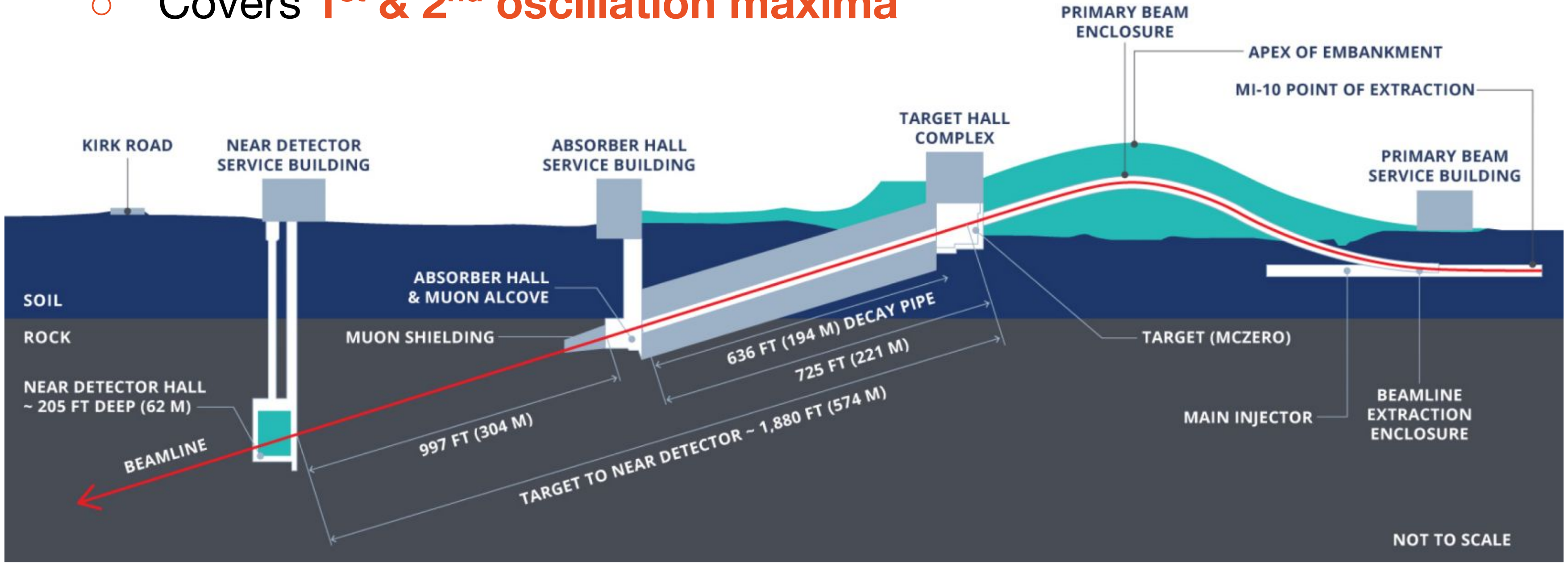
Neutrino beam

- DUNE neutrino beam made from proton beam:
  - Phase 1: **1.2 MW**
  - Phase 2: Upgrade to **> 2 MW**

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

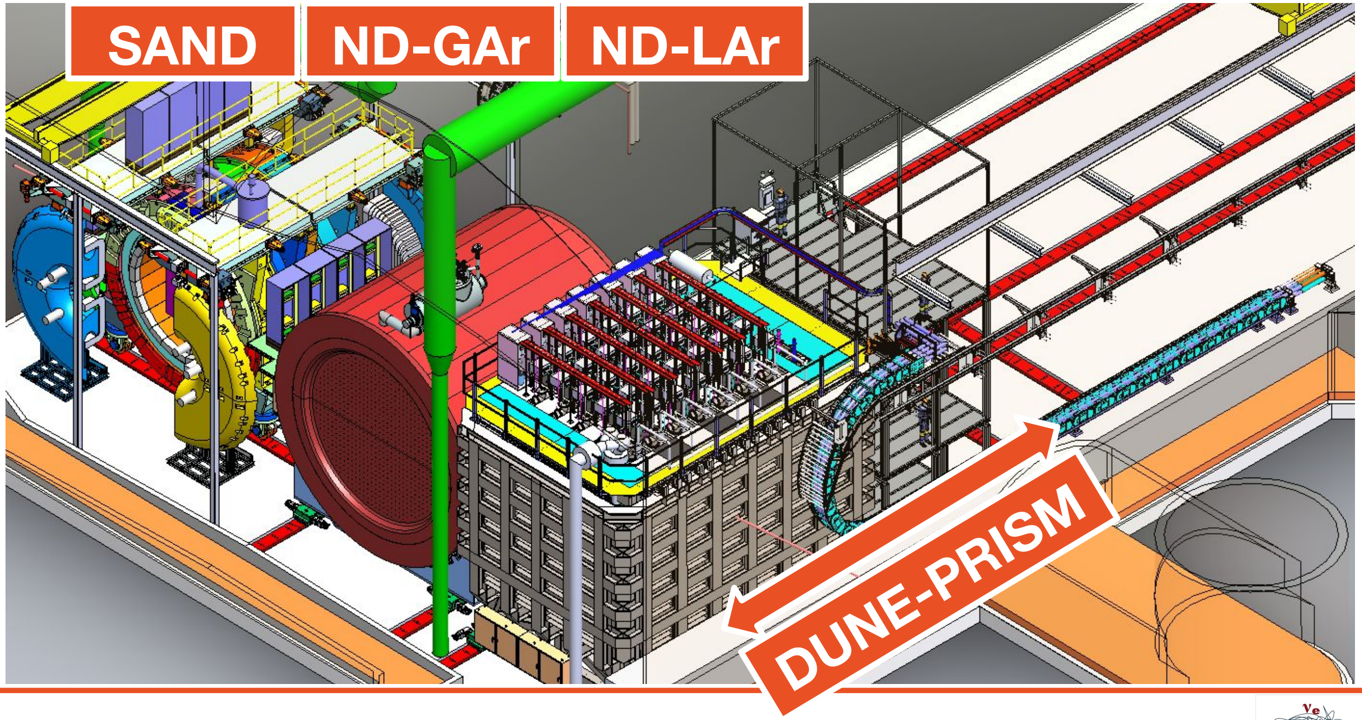




Near detector (ND)

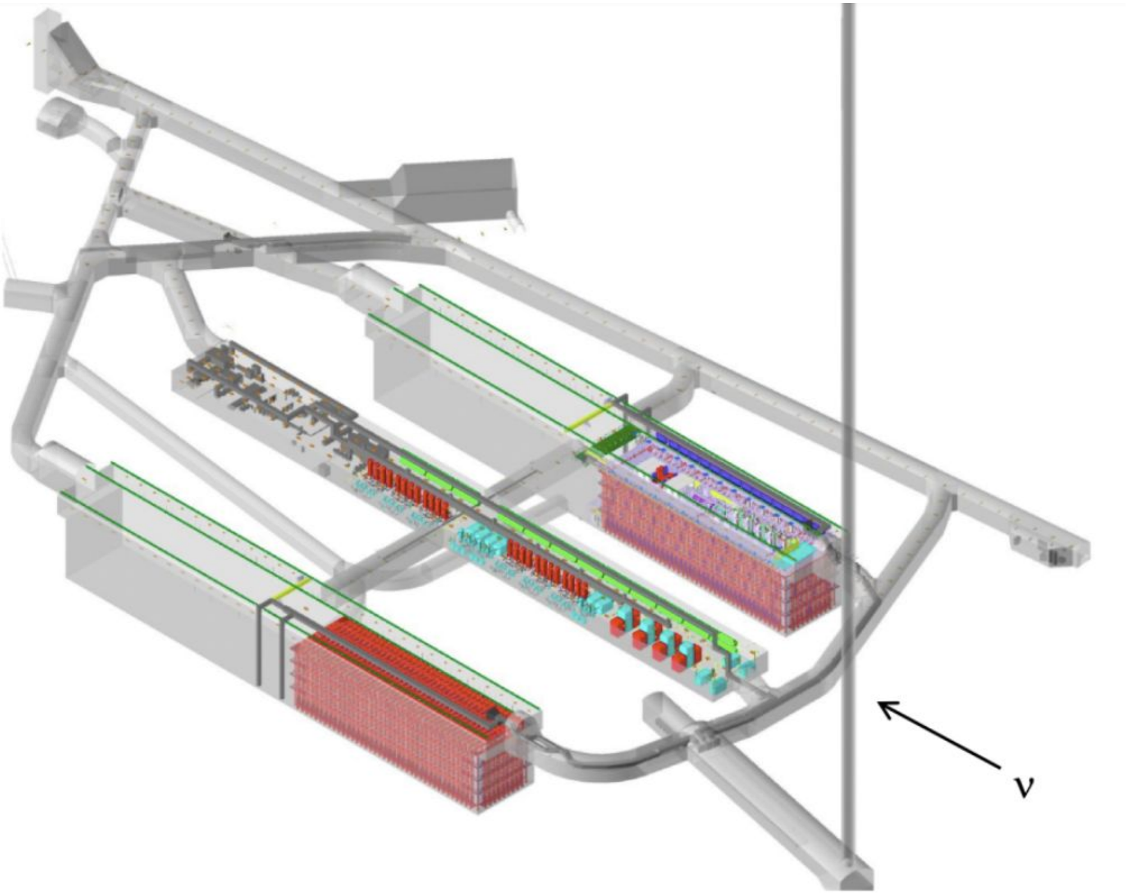
- **Multi-component**: Liquid argon TPC (**ND-LAr**), Gaseous argon TPC (**ND-GAr**), On-axis beam monitor (**SAND**)
  - **Phase 1 —> Phase 2** : Temporary Muon Spectrometer (TMS) —> ND-GAr
  - Characterisation of beam as well as **constraining cross-section uncertainties**

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



Far detector (FD)

- Far detector is located **1500 m** underground at SURF
- Consists of **4 modules** each with a total mass of **17 kt**
- Modules 1,2 and 3 will be Liquid Argon TPCs (LArTPCs)
- Module 4: “Module of Opportunity”
  - Several technologies being considered



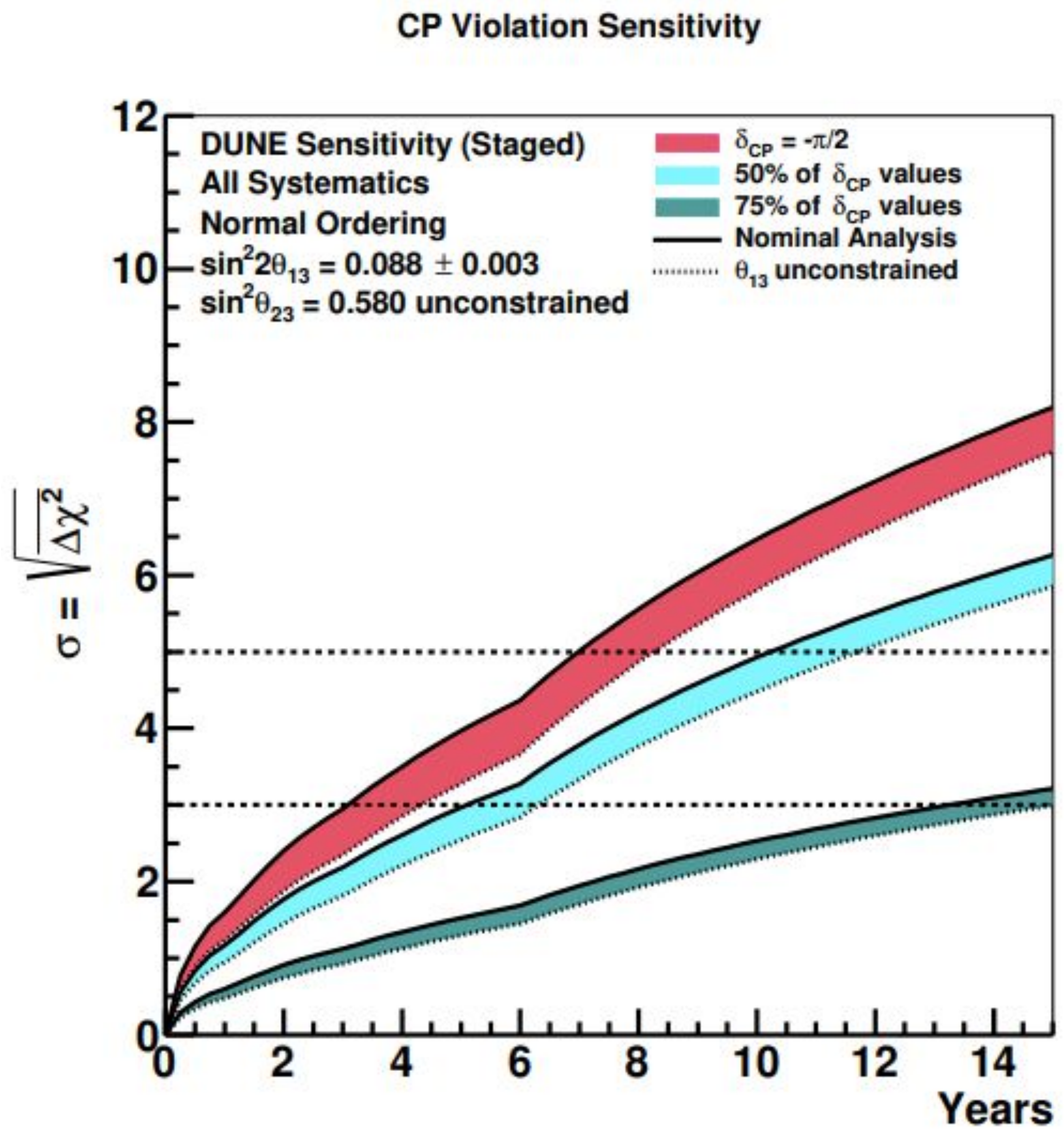
How do long-baseline analyses work?

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

- Measure an event rate —> convolution of **oscillations** and **systematics models**
- Near detector assumed to have **no oscillations** —> **constrain the systematics**
- Far detector has far fewer events and oscillations —> **apply systematic constraints**

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)



FD TDR Analysis

- Current DUNE sensitivities produced using

This talk focuses on **new Bayesian sensitivity studies** using a Markov Chain Monte Carlo framework - **MaCh3**

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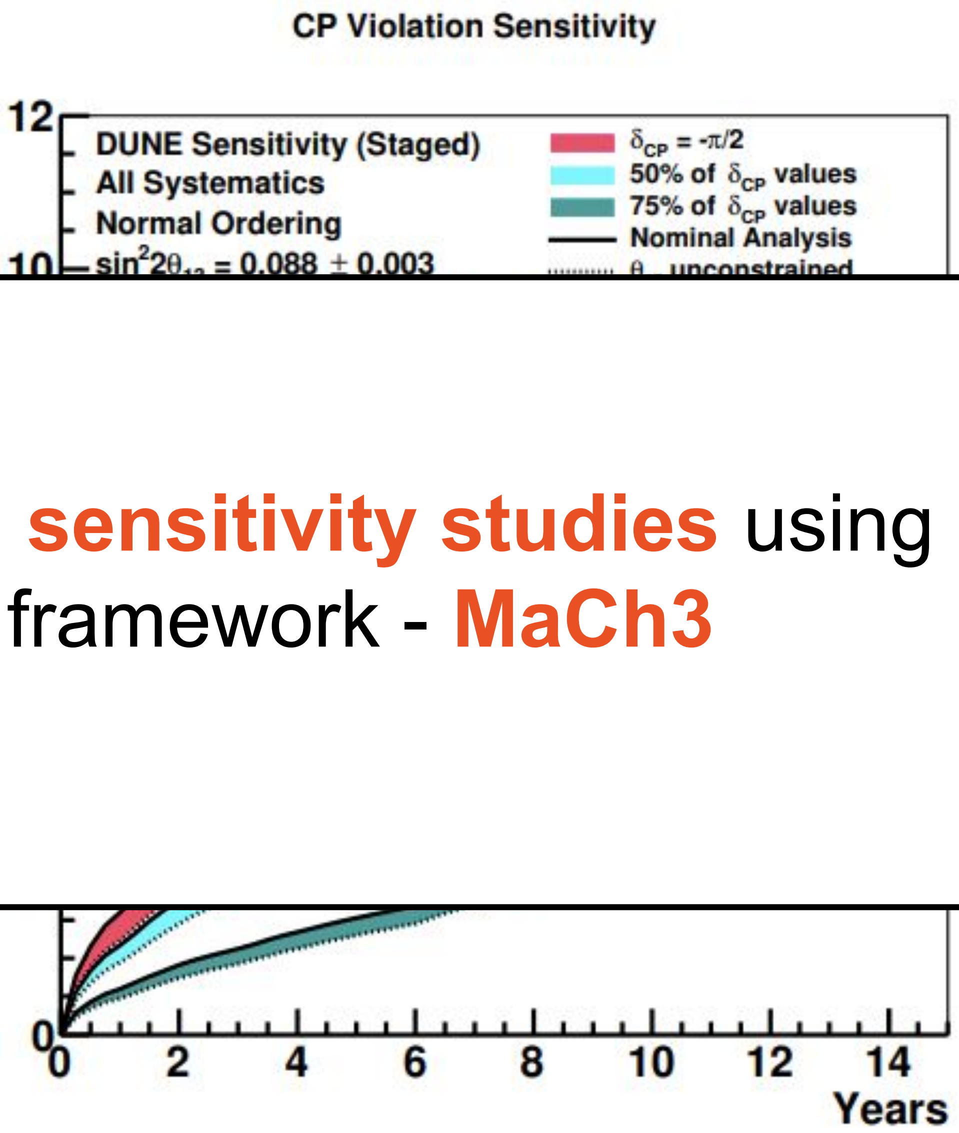

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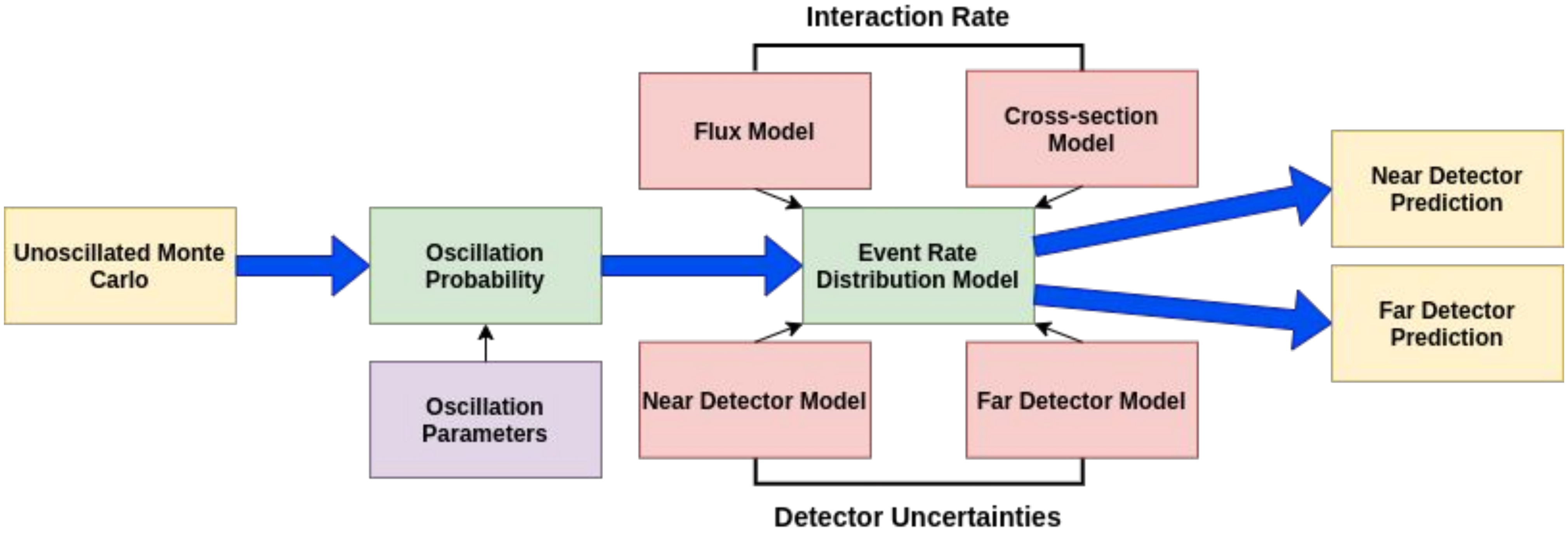
What is MaCh3?

- **Markov Chain Monte Carlo**-based **Bayesian fitter** with integrated likelihood calculator

- In use for T2K, T2K+NOvA, T2K+SK atmospherics, DUNE and Hyper-K

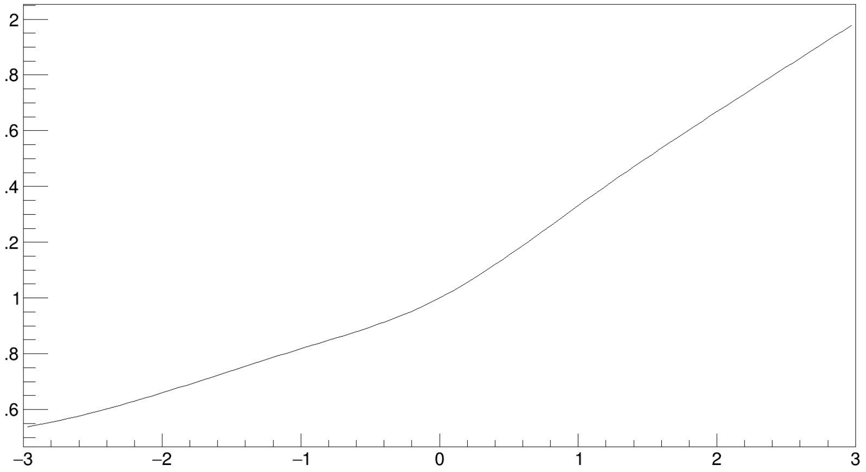
- We usually perform a **joint ND+FD** fit but can also fit ND separately and use post-ND-fit-constraints in a FD fit



Systematic Implementation

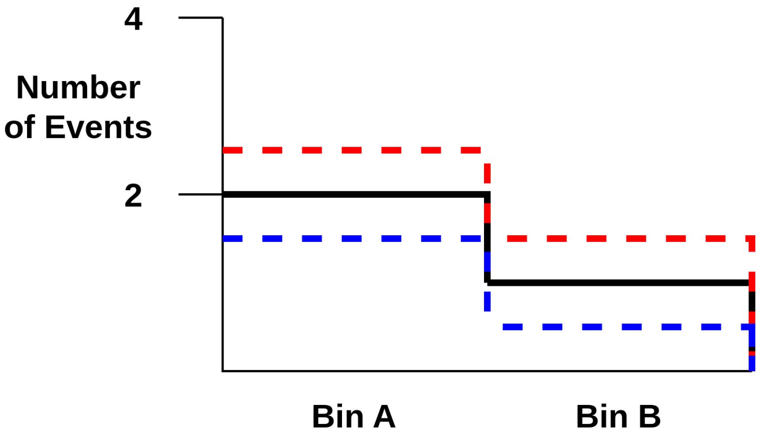
- Current systematic models **aren't sophisticated enough to handle the high statistics**
- We need to model a complex/degenerate likelihood space -> **different types of systematics:**

Splines



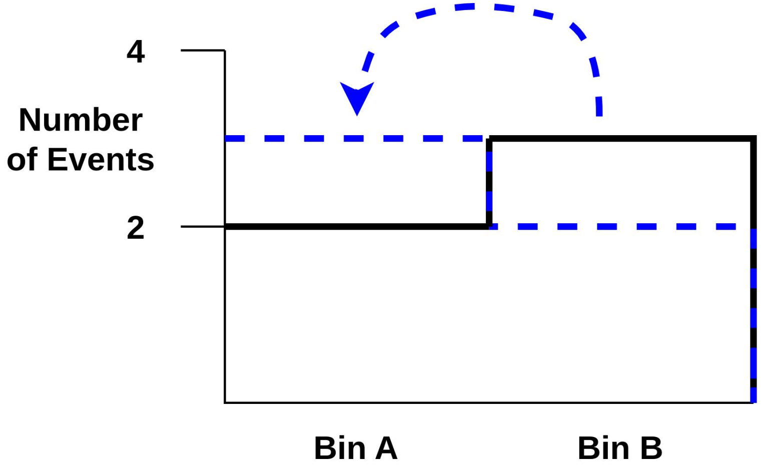
- Continuous response functions using piecewise cubic interpolation
- Binned or **event-by-event**
- Cross-section parameters

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

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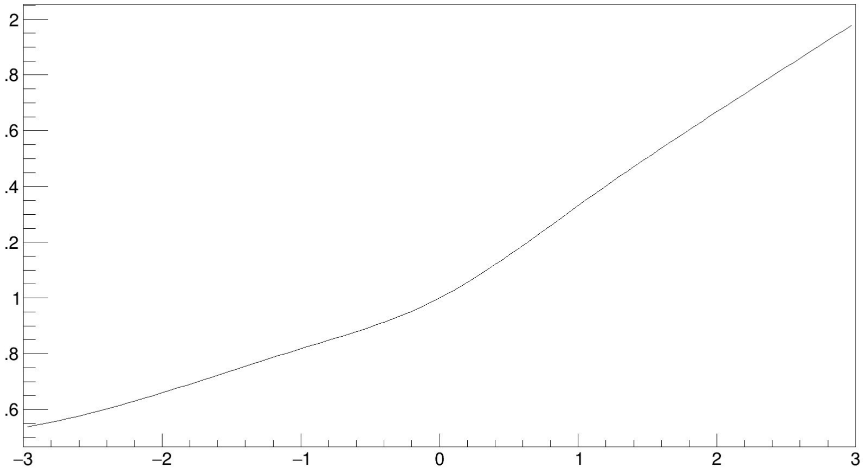

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Normalisation

MaCh3 keeps all event information during a fit

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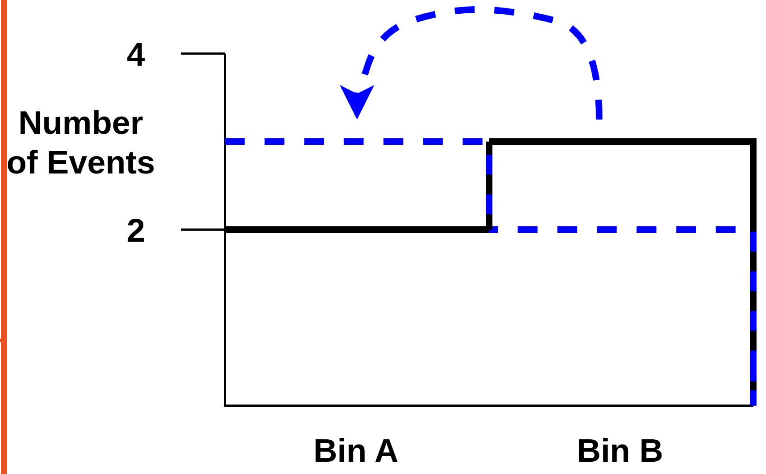

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Asimov Fit Details

- First **simultaneous** fit to FD and ND samples

- **NuFit 4.0 NH** Asimov point chosen
  - $\sin^2(\theta_{23}) = 0.580$, $\sin^2(\theta_{13}) = 0.0224$, $\Delta m_{32}^2 = 2.525\text{x}10^{-3}\ \text{eV}^2$, $\delta_{CP} = -2.498$
  - **Flat priors** in **oscillation parameters of interest** (above)
  - Solar constraint used for $\sin^2(\theta_{12})$ and Δm_{21}^2

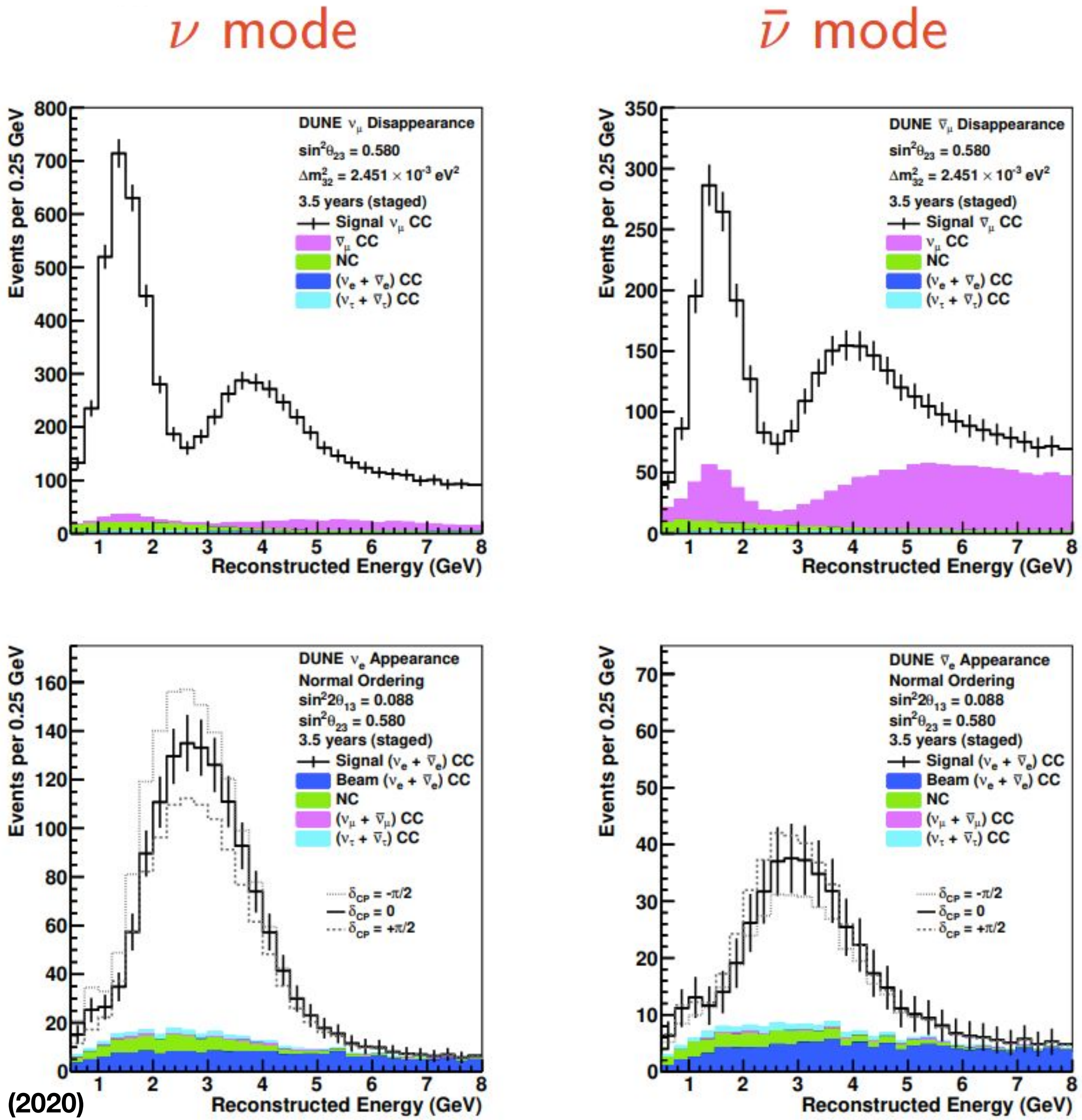
- Markov chain ran for **180 million** steps

- Contains full systematic treatment **(288 systs)** for **xsec (55 systs)**, **flux (204 systs)** and **FD detector (24 systs)**
  - **ND detector systematics** included by adding **covariance matrix** to likelihood calculation

- Using **nominal staged 7 year exposure (336 ktMWyr)** and **without reactor constraint**

Samples

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



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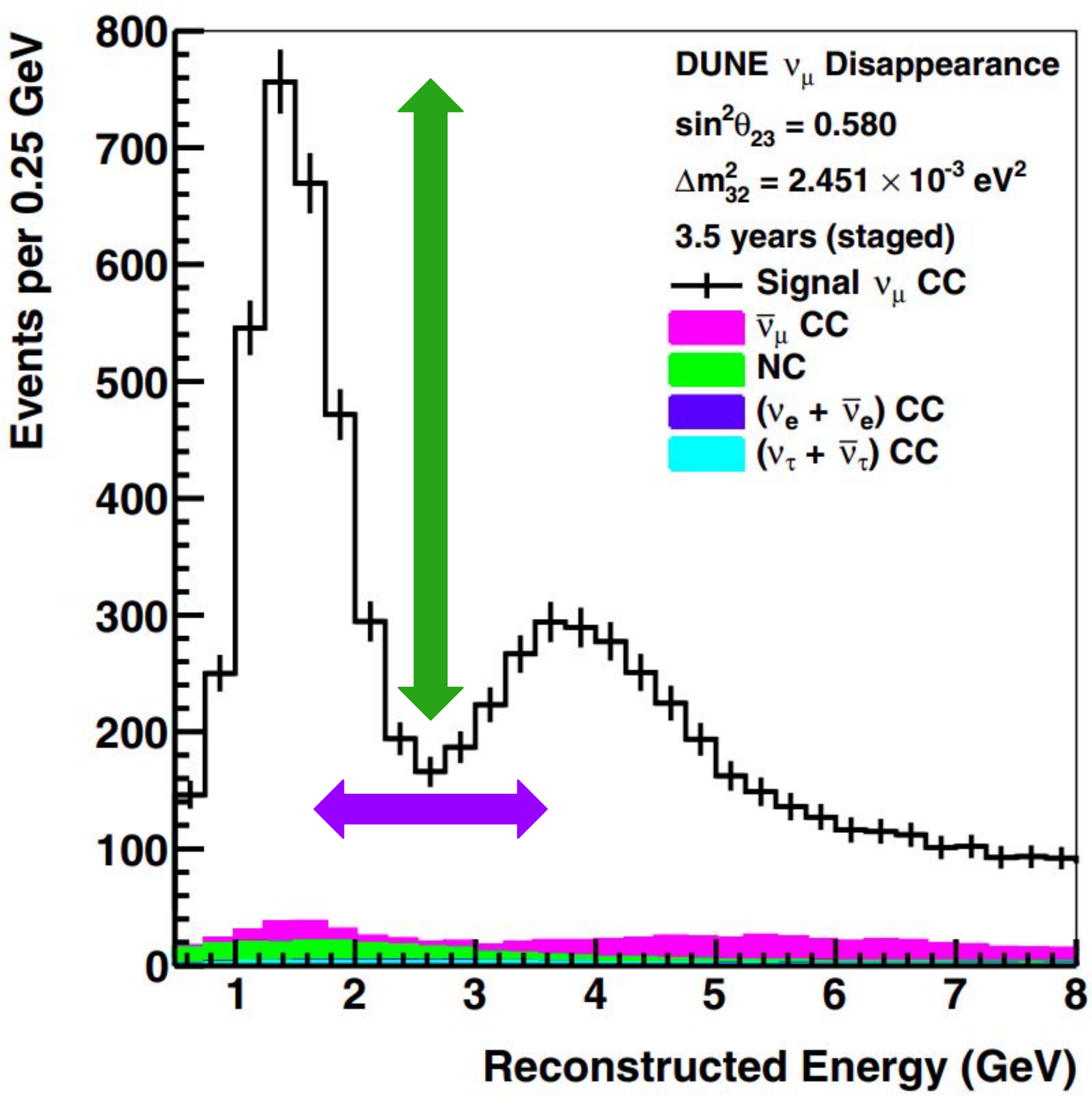

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MaCh3 Imperial College London DUNE

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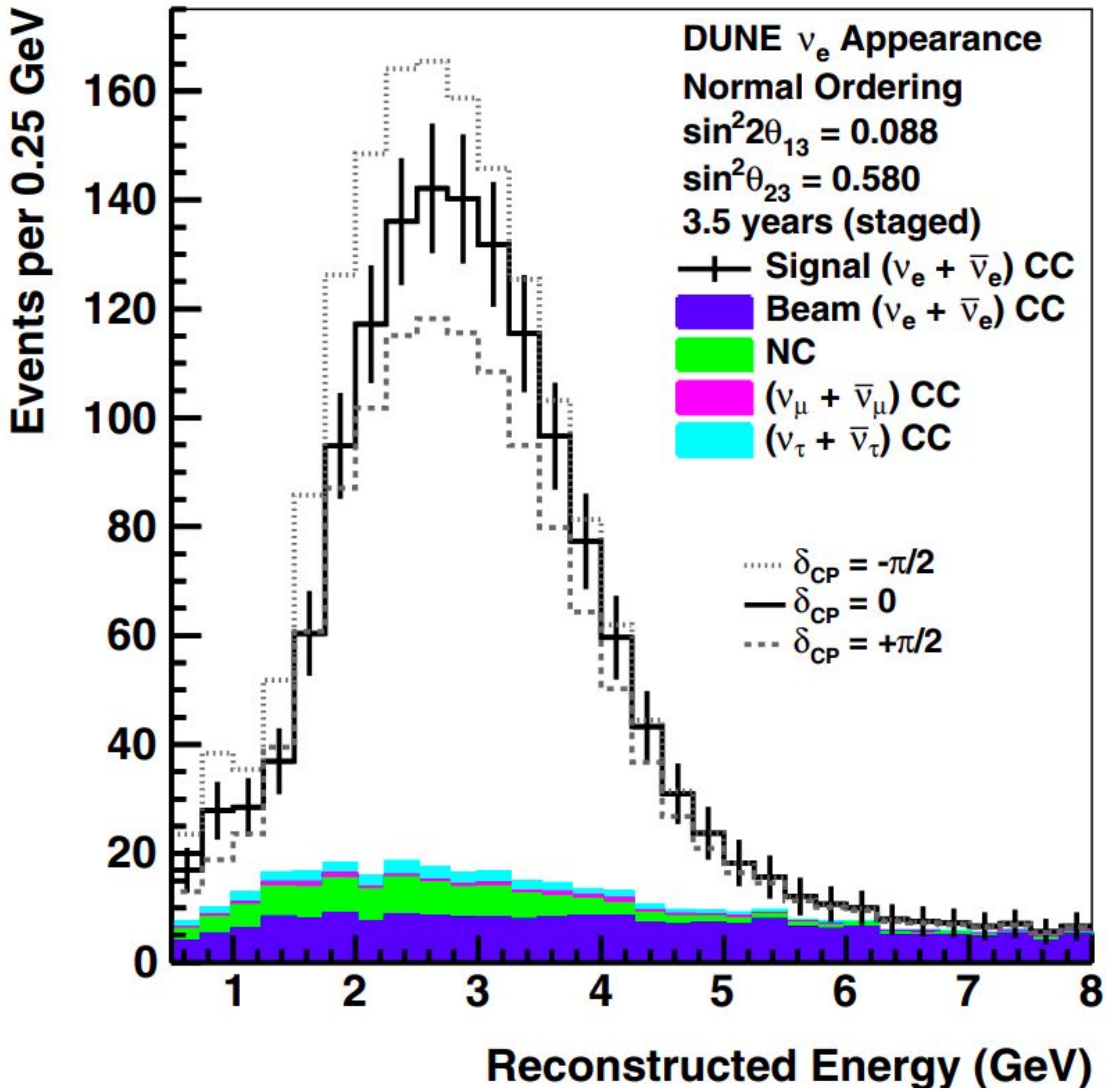

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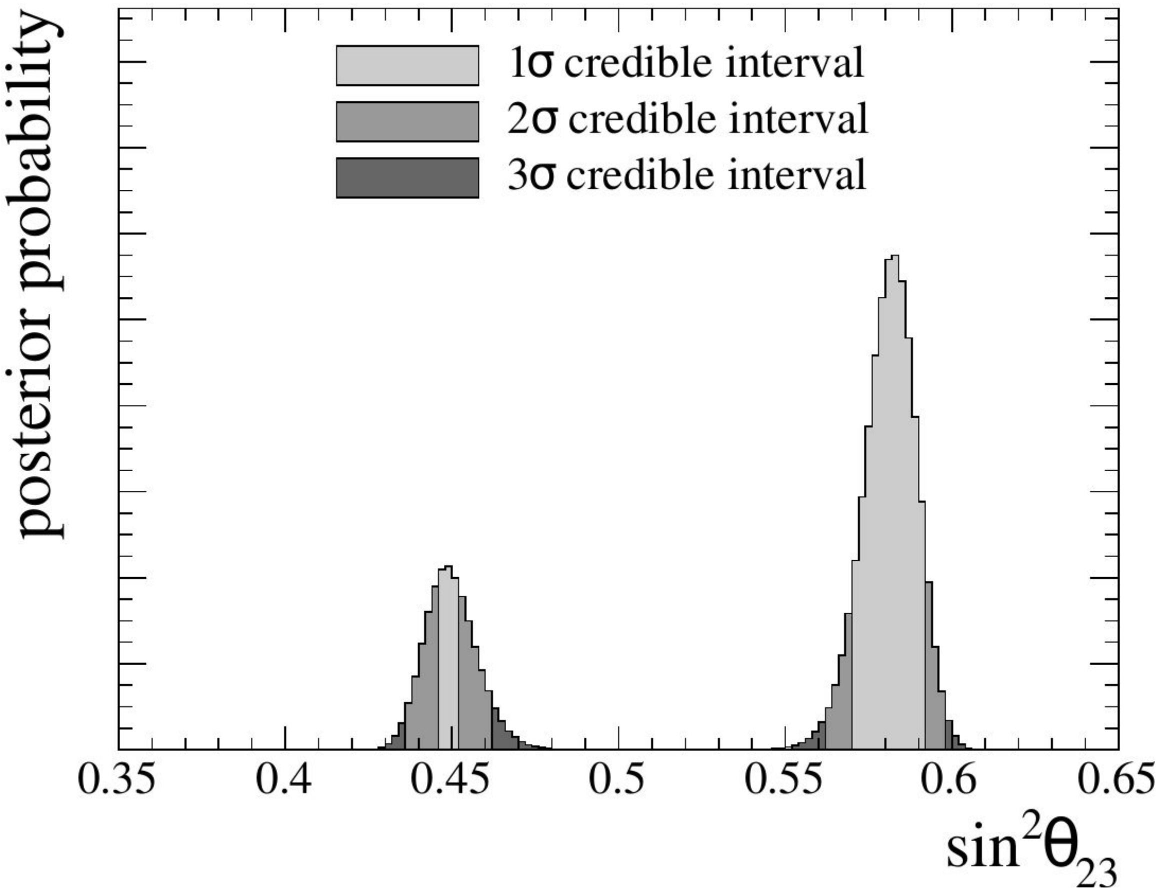
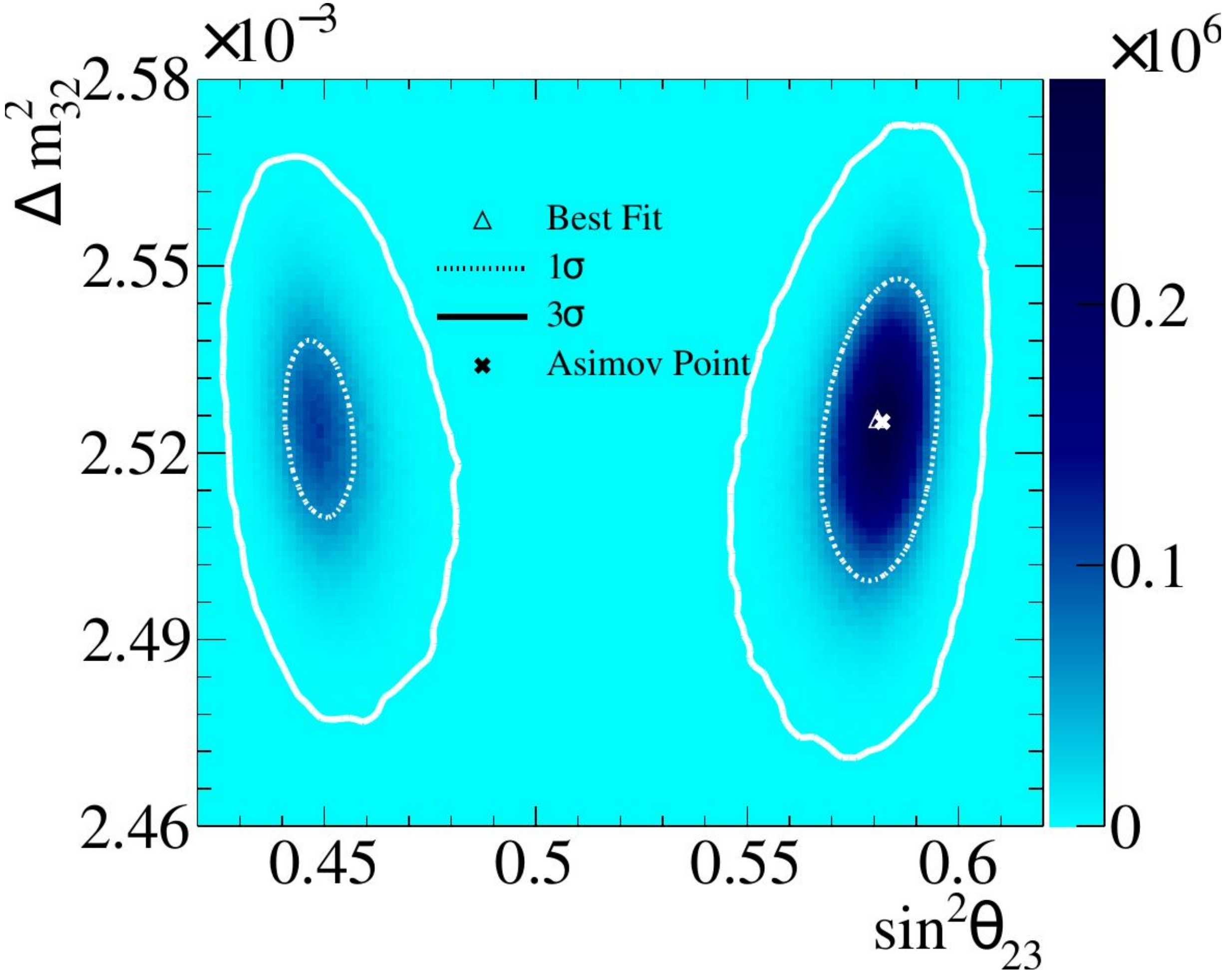
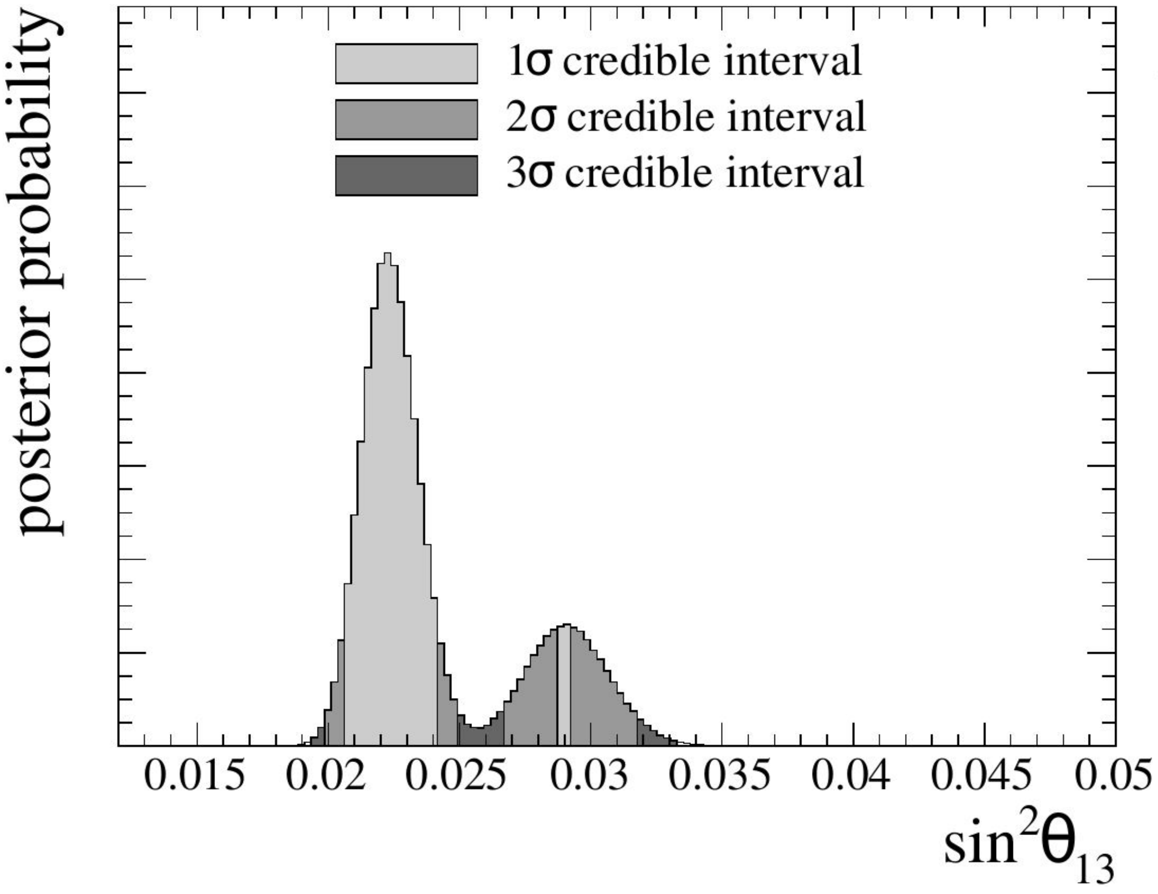
θ_{23} Sensitivity

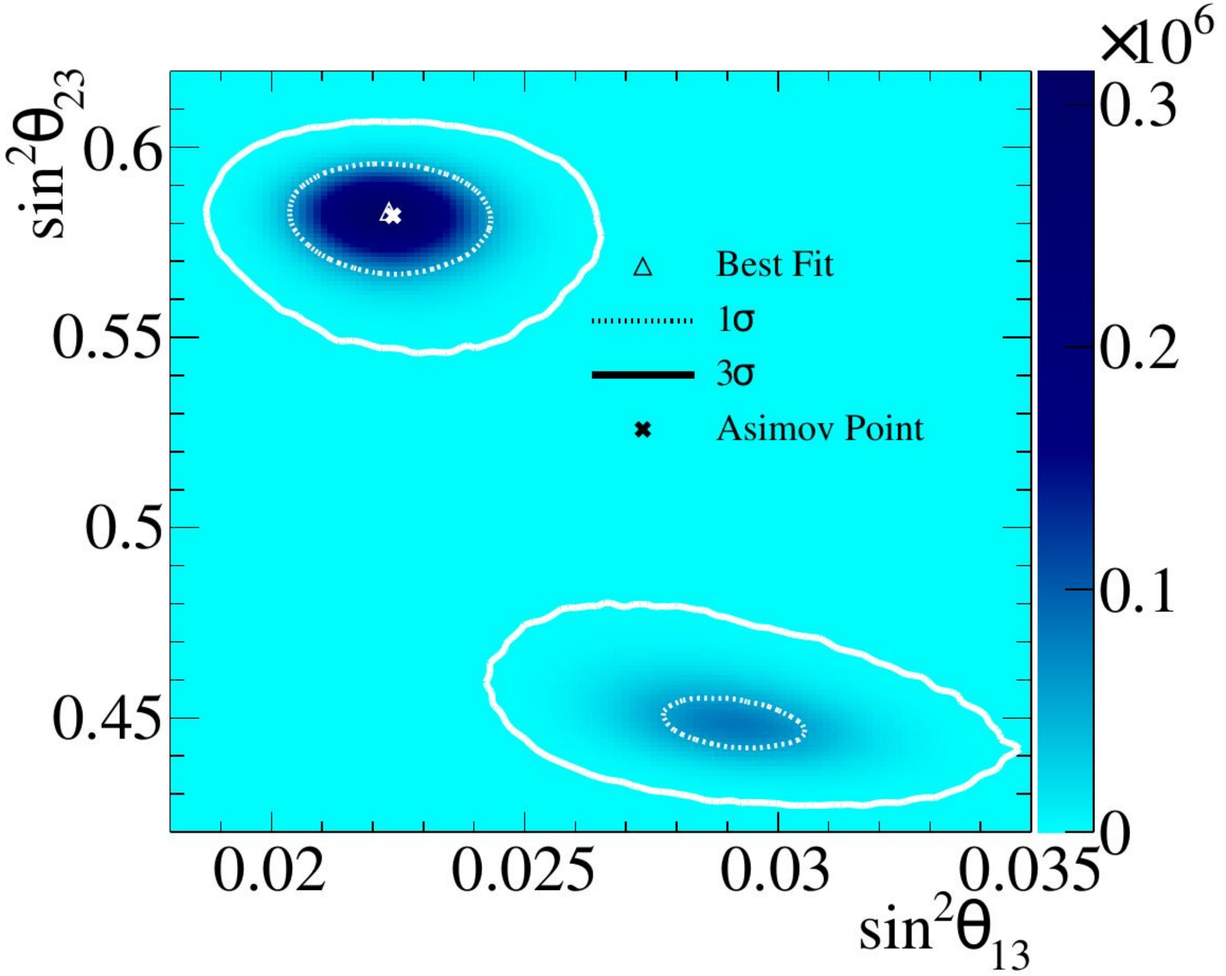




- Both θ_{23} octants being evaluated - **correct octant chosen**
- **No posterior in IH**

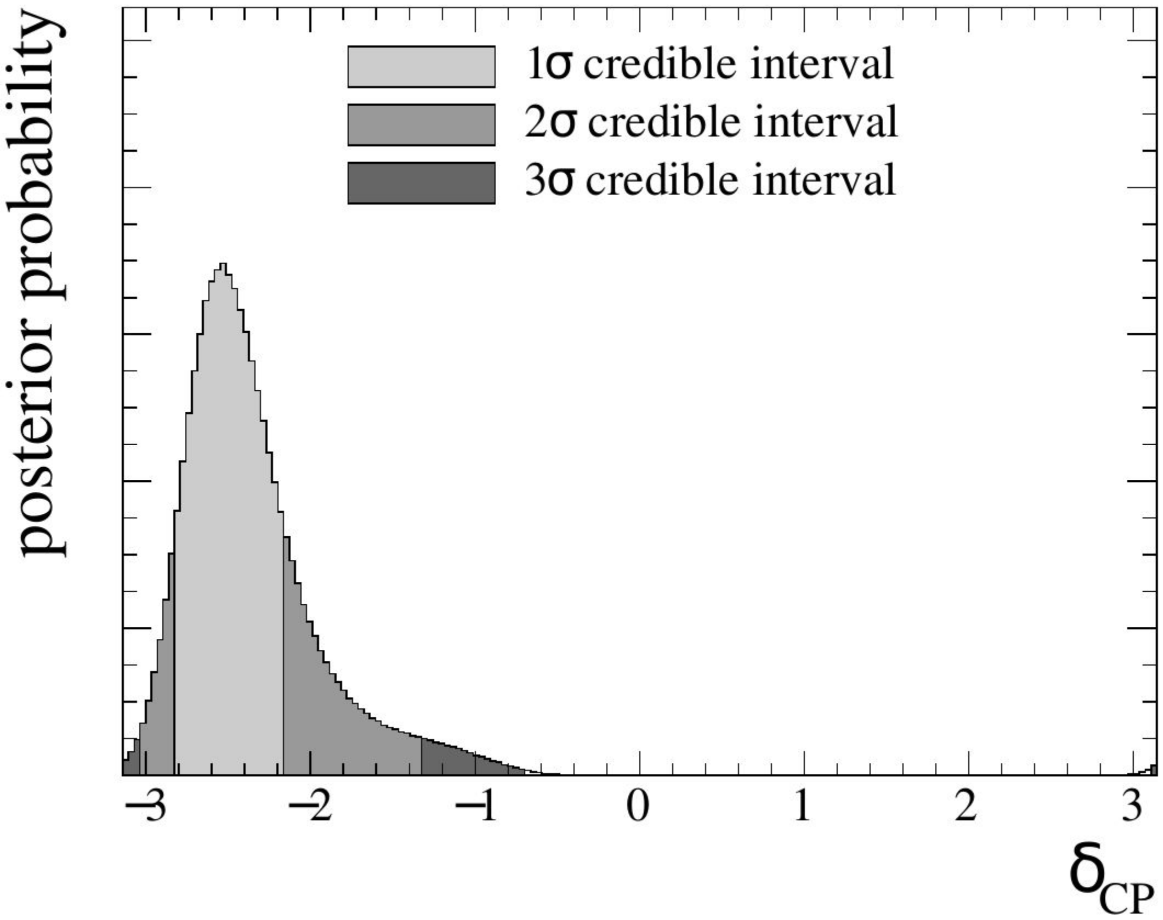
θ_{13} Sensitivity

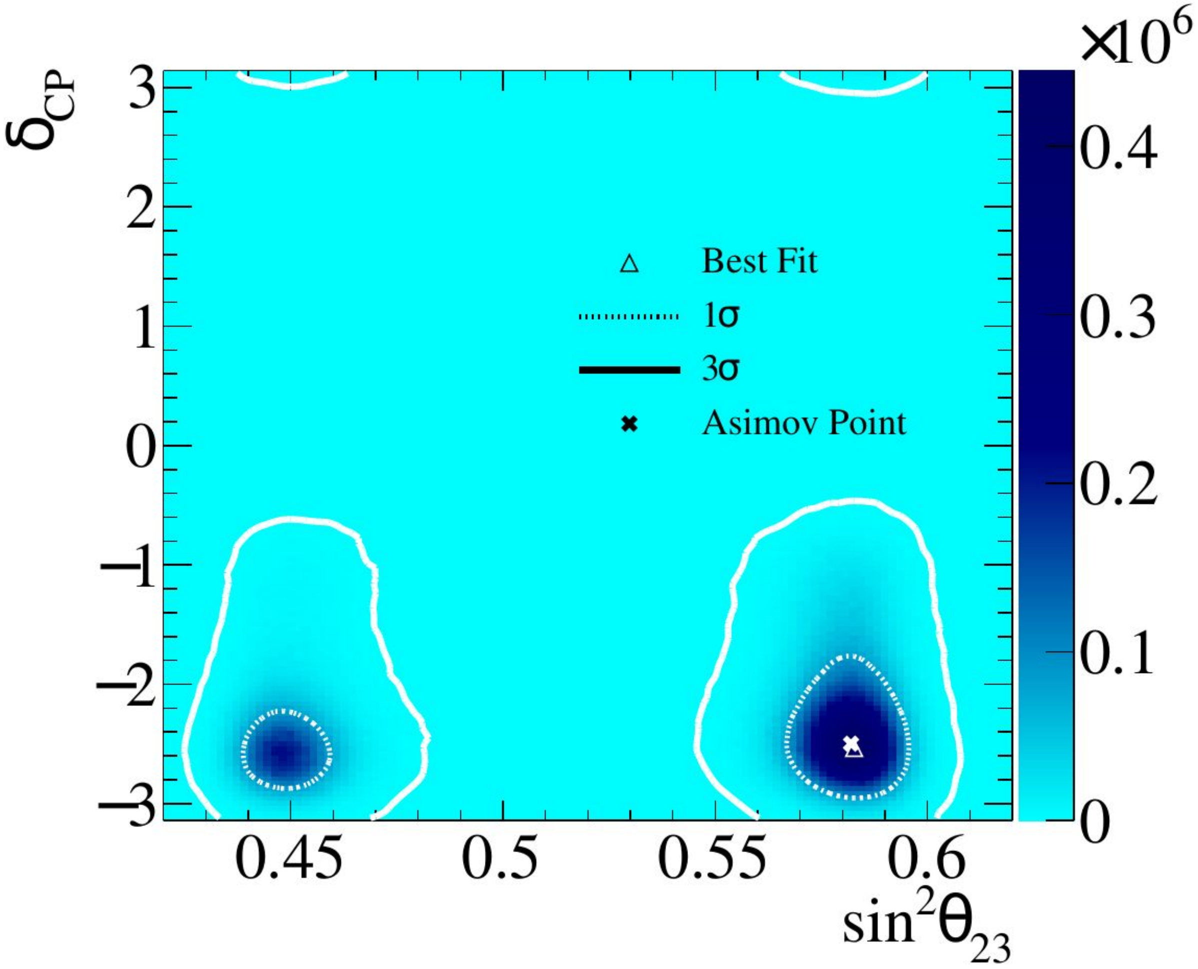




- Some degeneracy in θ_{13} -> caused by θ_{23} octant

δ_{CP} Sensitivity

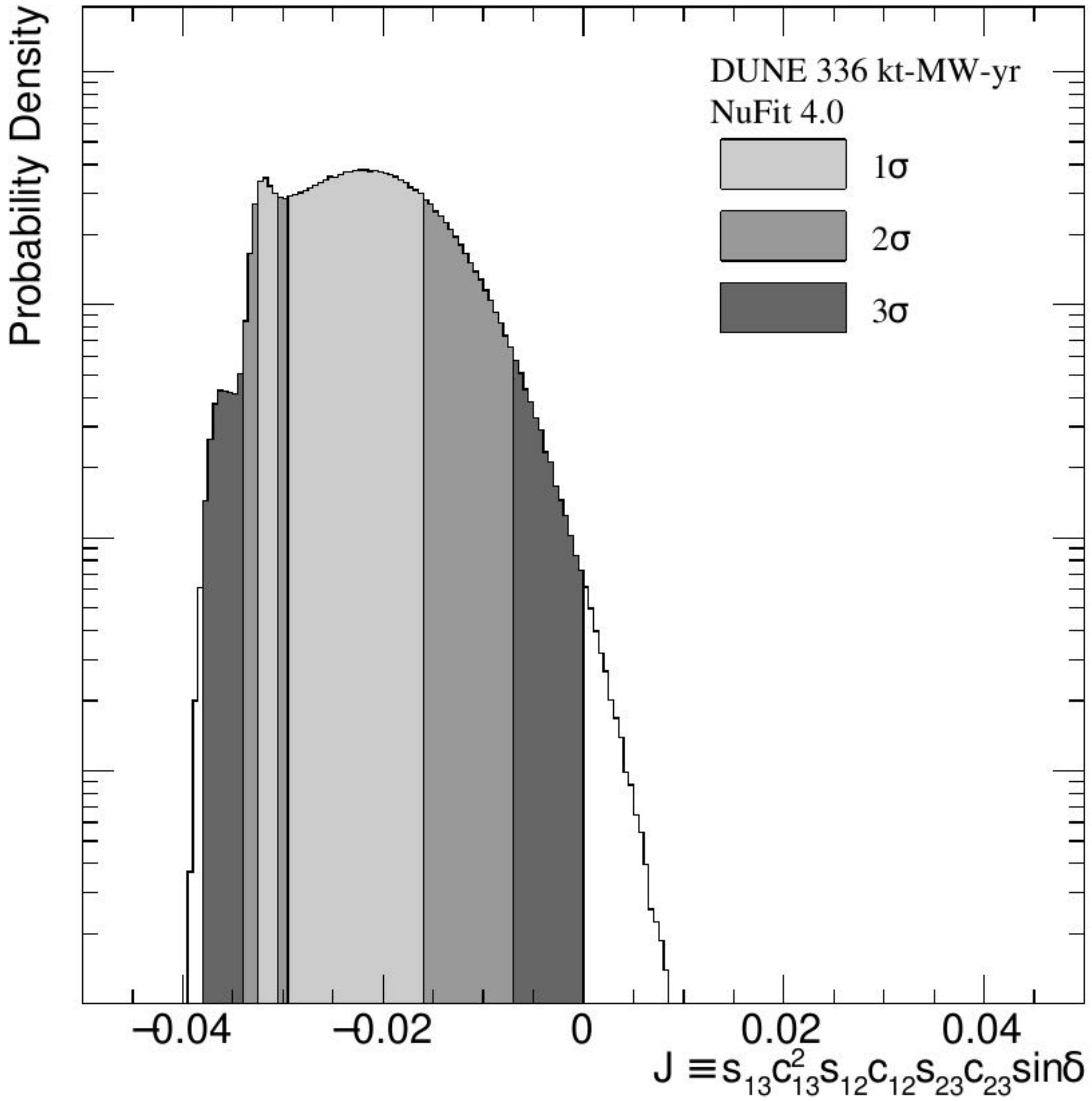




- CP-violation significance **agrees with TDR analysis** for **this exposure**
- Tail towards 0 caused by δ_{CP} octant degeneracy

Jarlskog Invariant

- The **Jarlskog invariant** indicates the magnitude of **CP violation**
- MaCh3 can produce a **Jarlskog invariant posterior distribution** without running another fit
- Value of 0 indicates **no CP violation**
- Irregularity in credible intervals likely caused by **θ_{13}** and **θ_{23} octant** degeneracy



Summary

- DUNE will enable **an exciting physics program** and aims to make **precise measurements** of the oscillation parameters

- **First Bayesian analysis of DUNE** has been performed using TDR inputs and better systematic treatment
    - **Results are consistent**

- Current sensitivity studies worked great for Asimov
    - **More accurate systematic treatment** required to ensure our model can describe the data

- Next steps: Run with **higher exposure** and include **more capable near detector samples**

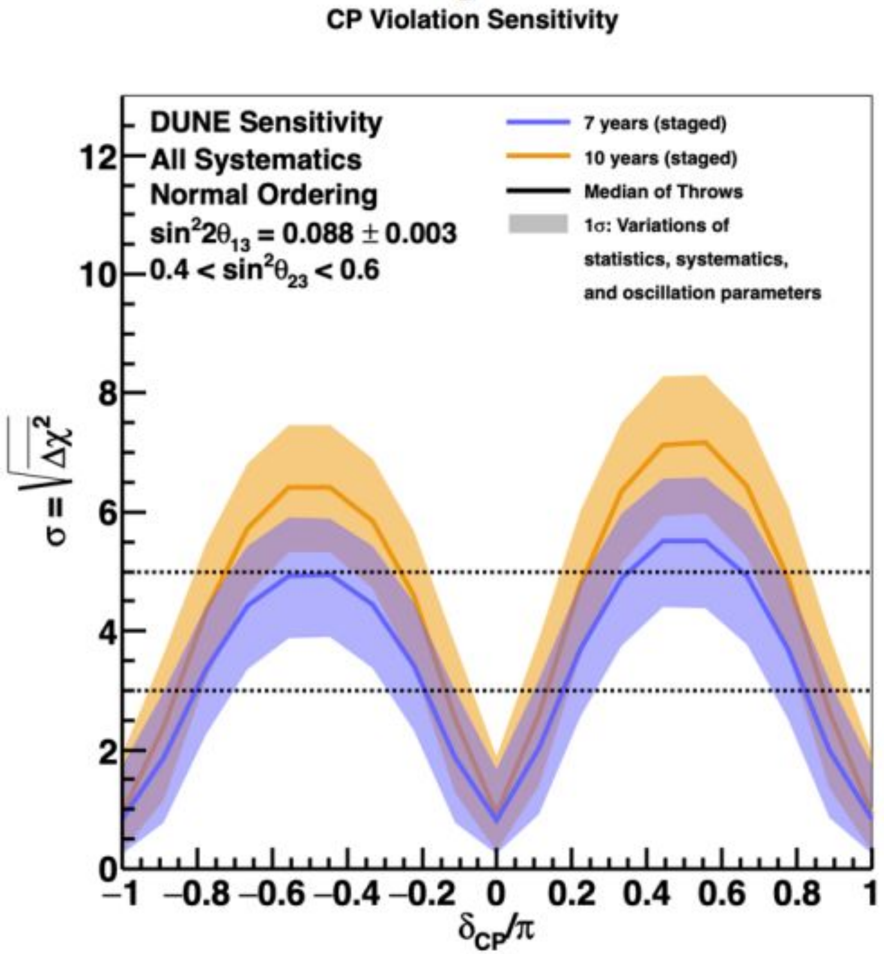
Back up

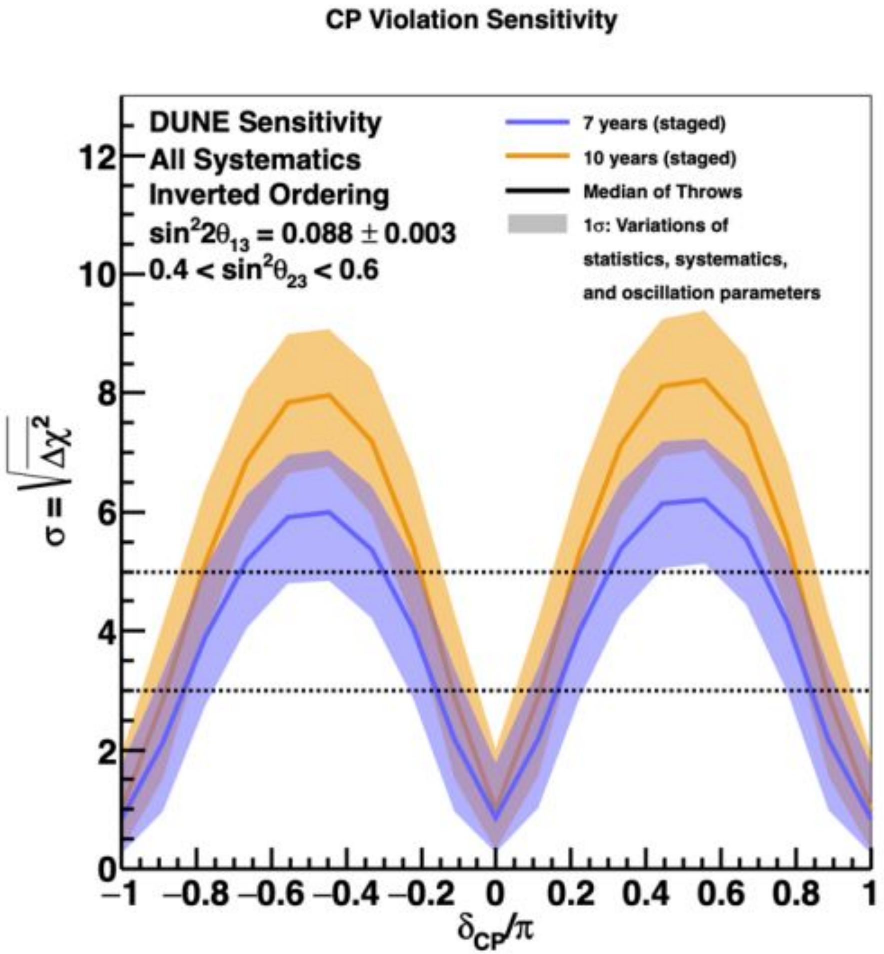
NuFit 4.0 Parameters

		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	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

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

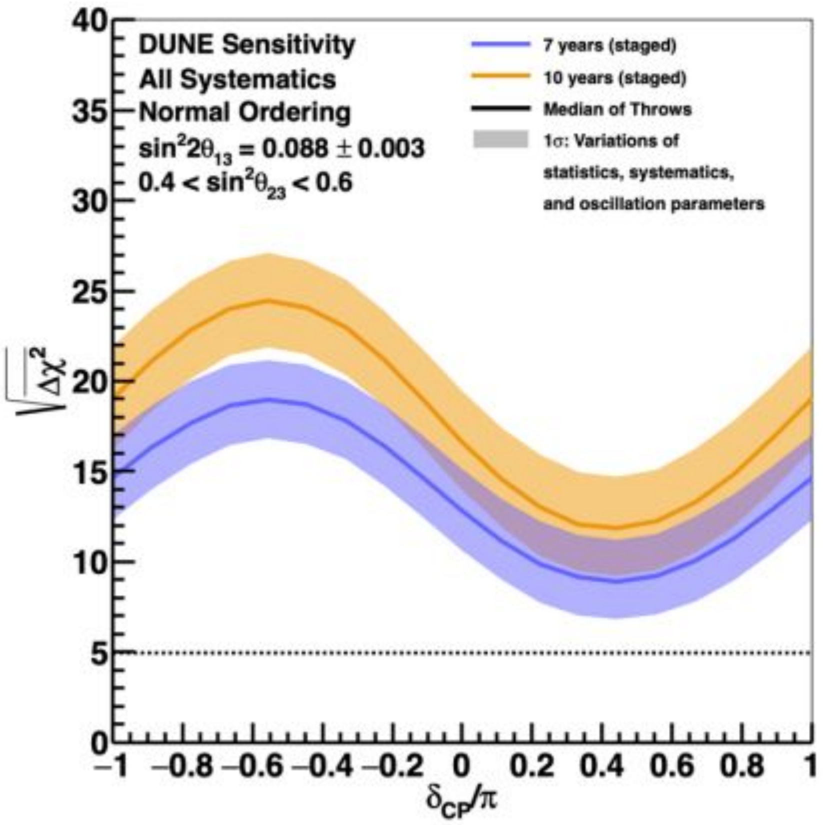
CPV Sensitivity

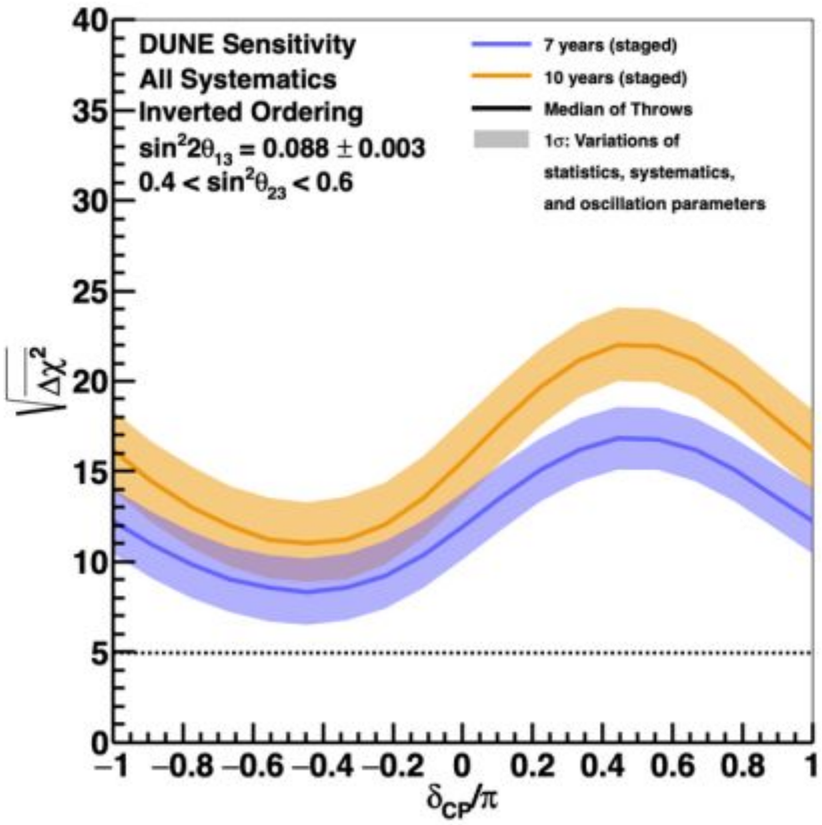




- After 10 years (staged), there is significant CP violation (**$\delta_{CP} \neq 0, \pi$**) discovery potential across true values of **δ_{CP}** and for both hierarchies

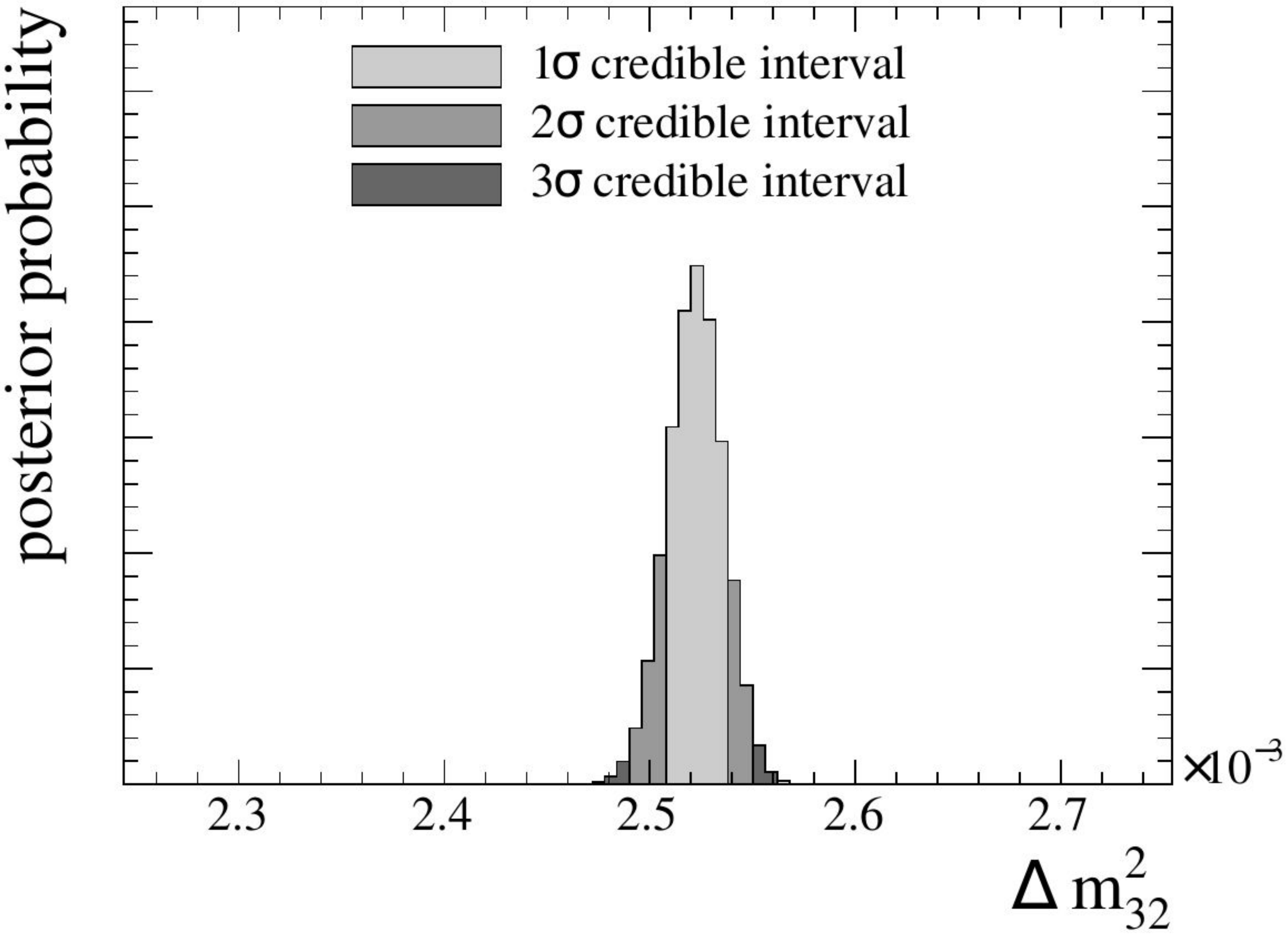
Mass Ordering Sensitivity





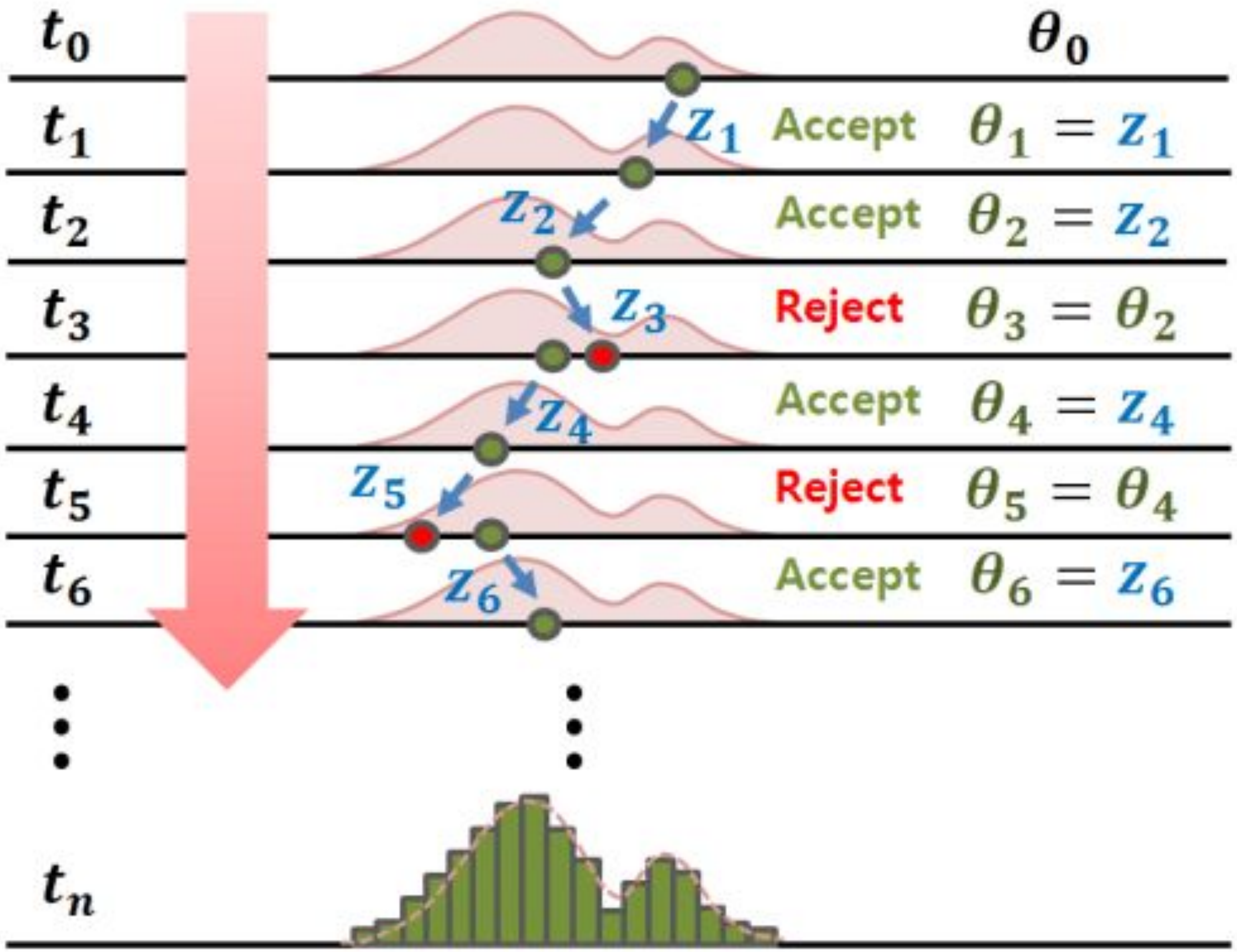
- Obtain a definitive answer for the mass hierarchy within 7 years (staged), regardless of the values of the other oscillation parameters

Δm_{32}^2 Sensitivity



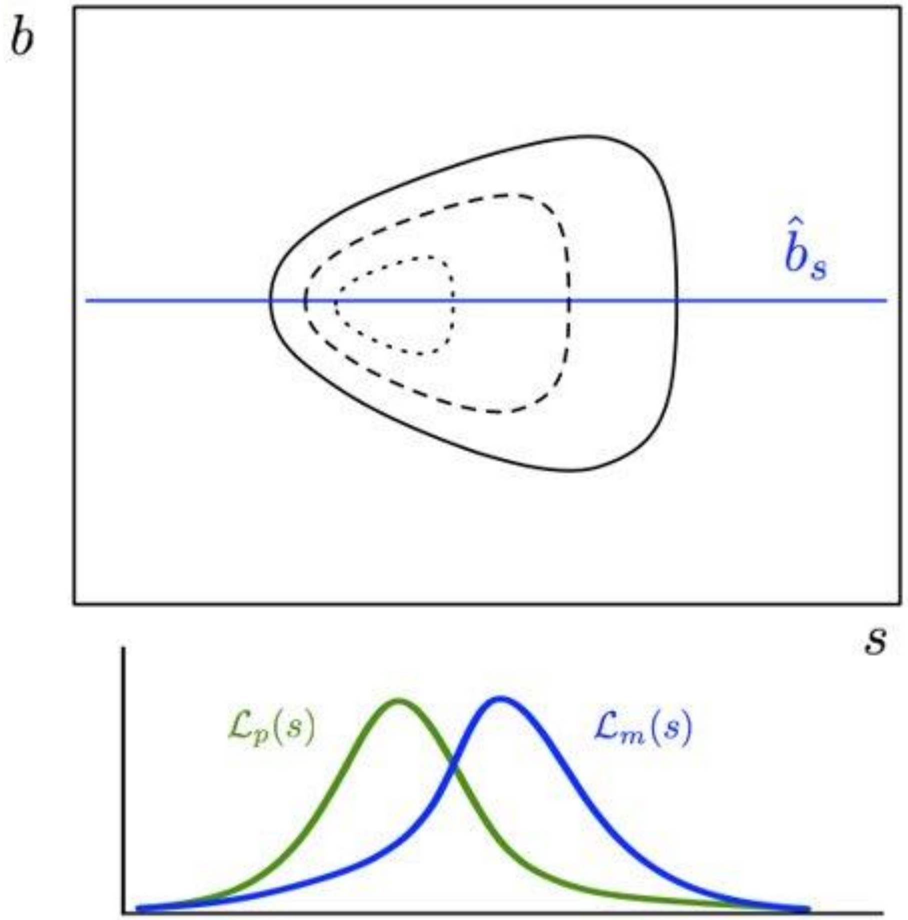
MCMC - Markov Chain Monte Carlo

- 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)



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:

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