A Bayesian Approach to DUNE's Sensitivity Studies

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RAL PPD Seminar Series
23rd April 2025

This Talk

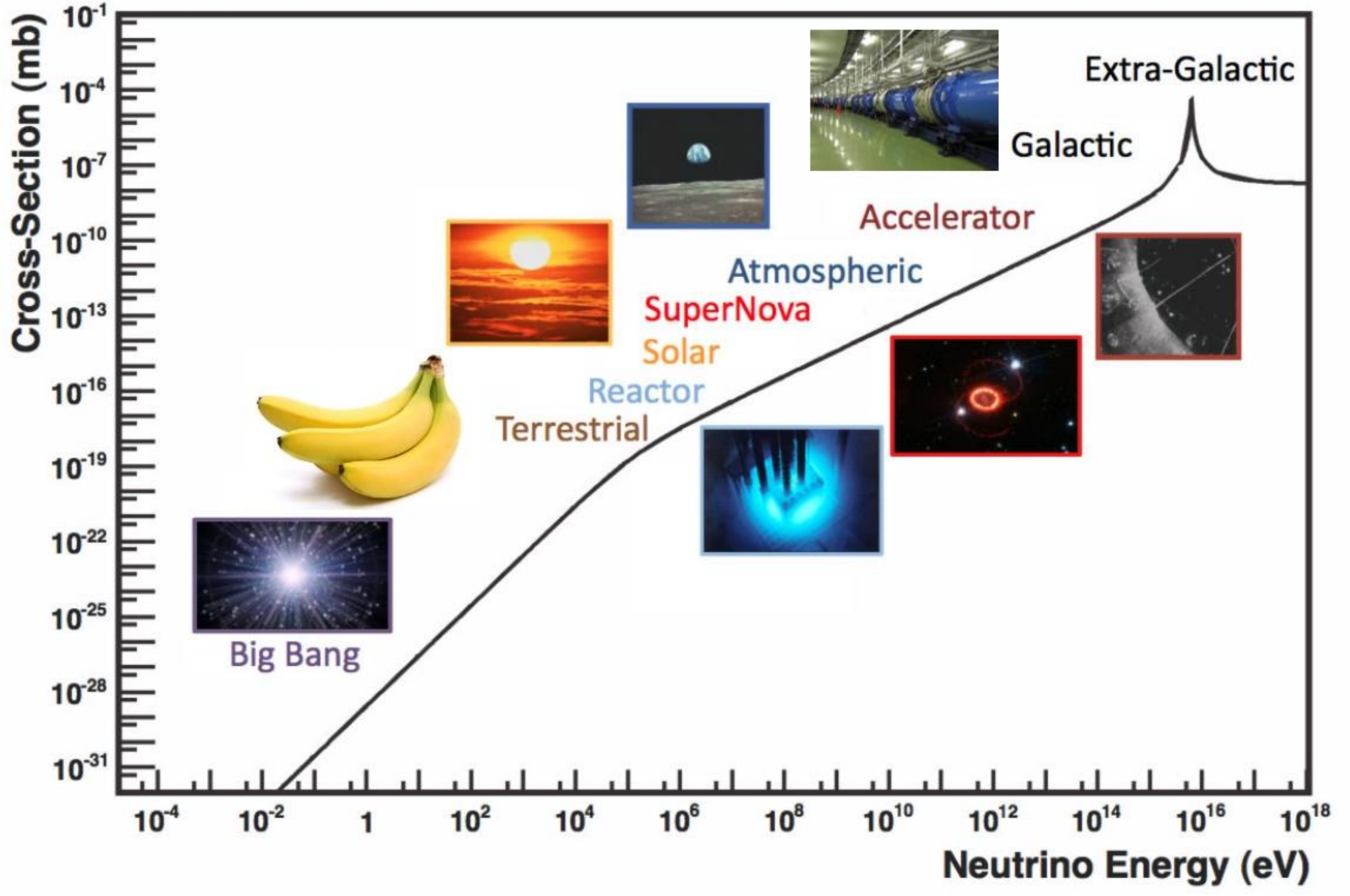
- Brief overview of neutrino oscillations

- Introduction to DUNE

- Bayesian DUNE Sensitivities

Neutrino Oscillations in a ν-tshell

Neutrinos Sources



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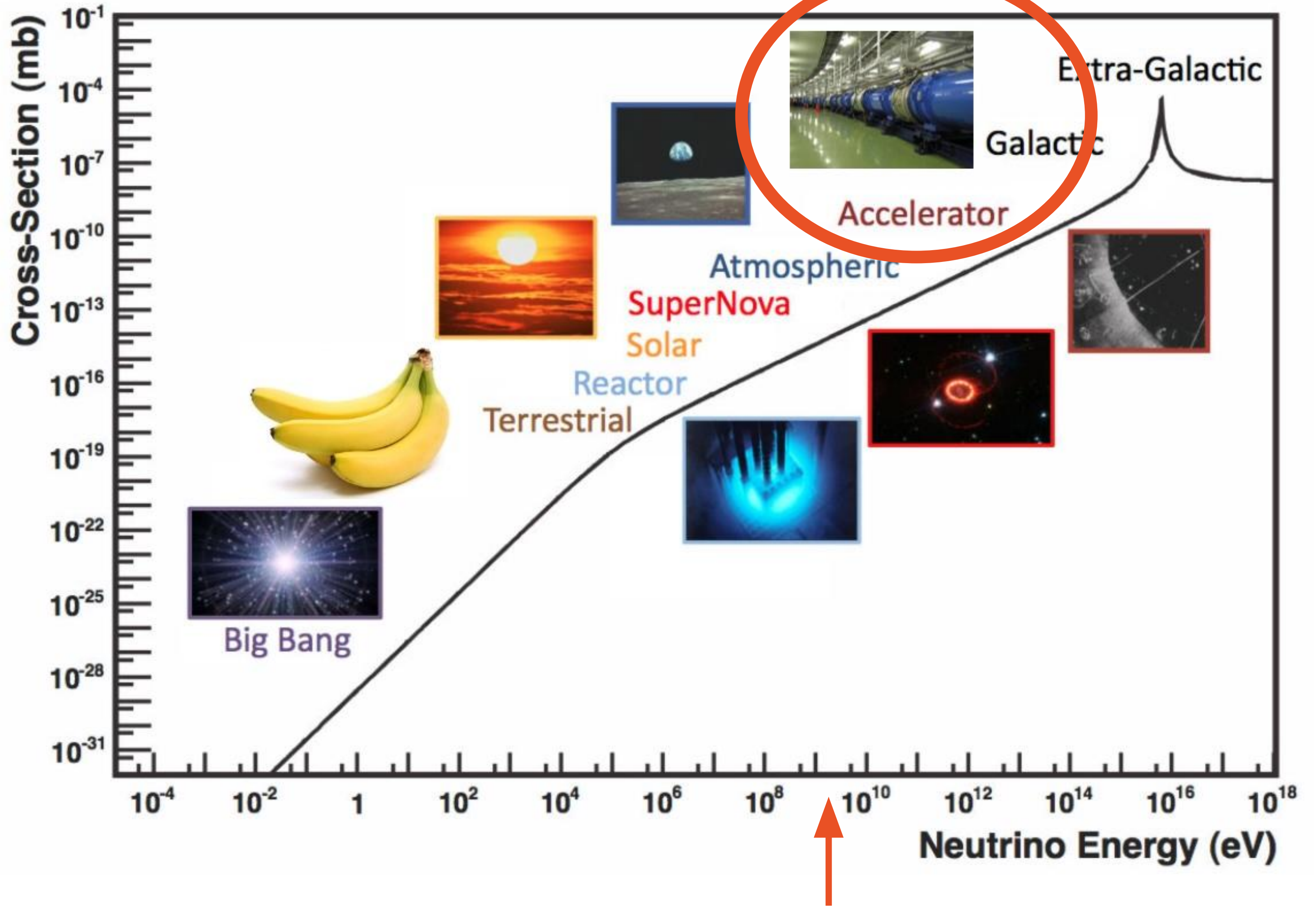

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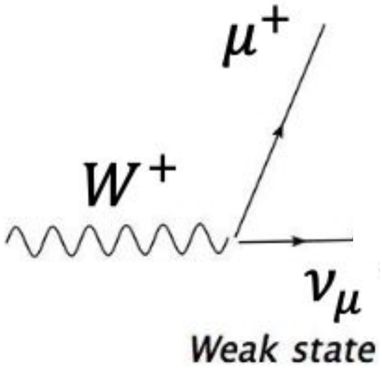
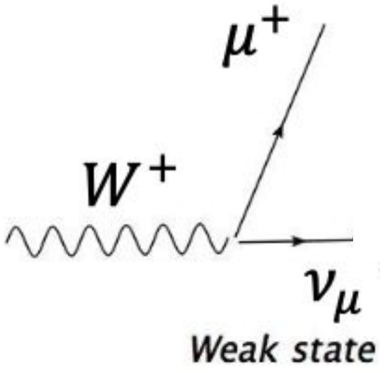
Neutrinos Oscillations

- Neutrinos are **produced** in particular **weak (flavour)** eigenstates: $\boldsymbol{\nu_e}$, $\boldsymbol{\nu_\mu}$, $\boldsymbol{\nu_\tau}$



Neutrinos Oscillations

- Neutrinos are **produced** in particular **weak (flavour)** eigenstates: ν_e , ν_μ , ν_τ
- These are linear combinations of mass eigenstates (ν_1 , ν_2 , ν_3)
  - Flavour eigenstates are related to mass eigenstates through a unitary mixing matrix: **PMNS matrix**



$$\boxed{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu 1}^* & U_{\mu 2}^* & U_{\mu 3}^* \\ U_{\tau 1}^* & U_{\tau 2}^* & U_{\tau 3}^* \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}$$

PMNS = **P**ontecorvo-**M**aki-**N**akagawa-**S**akata

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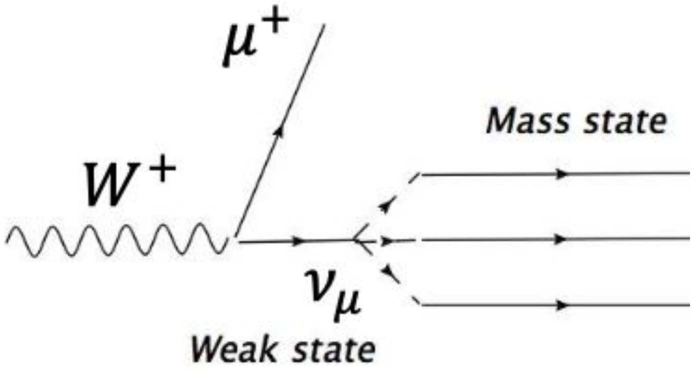

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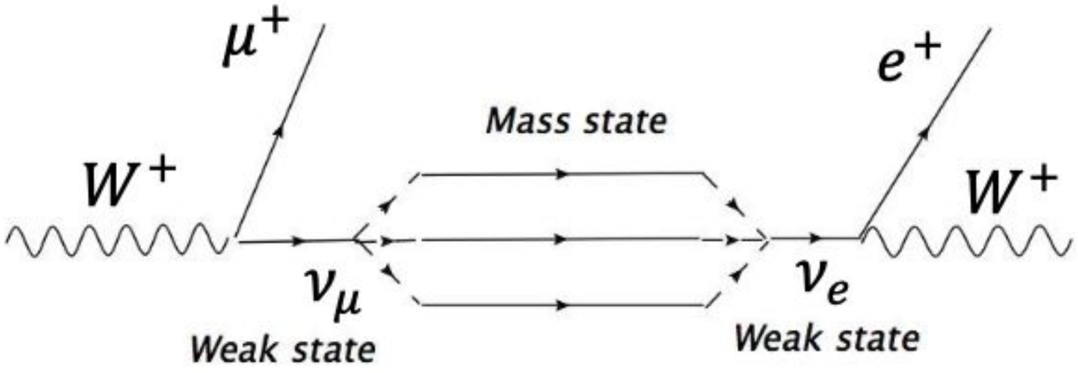
    - Flavour eigenstates are related to mass eigenstates through a unitary mixing matrix: **PMNS matrix**
- Neutrinos propagate in their mass eigenstates → **loss of unique flavour identity**
- When the neutrino interacts → collapses back to **weak state** → **probability** of a given flavour depends on **mass state mixture**



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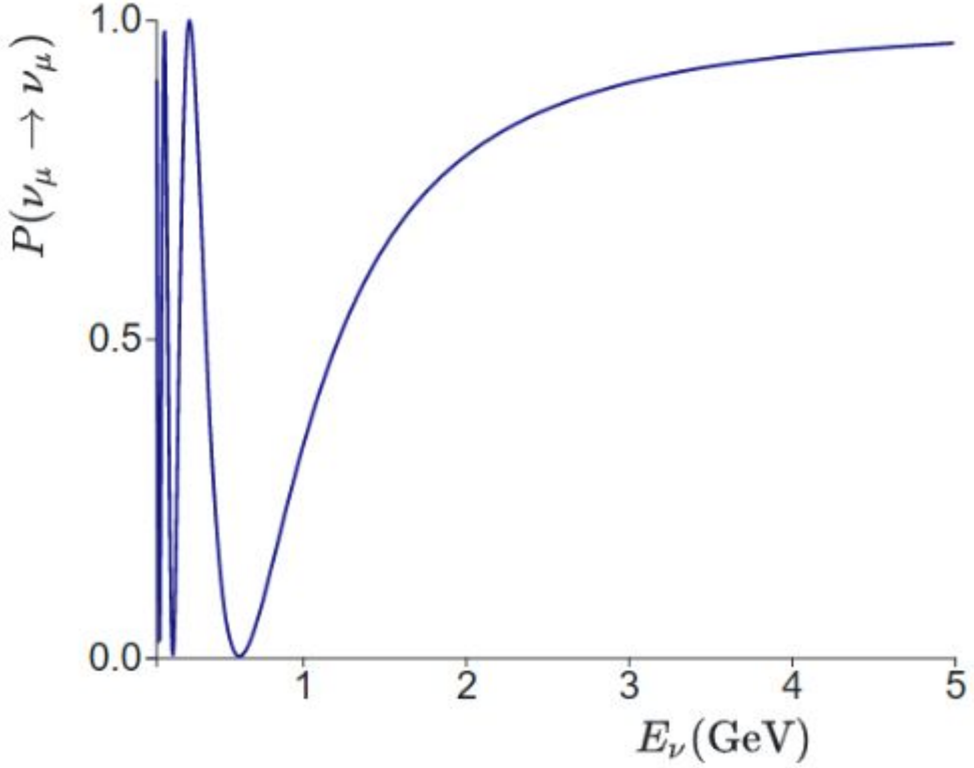
Neutrinos Oscillations

- Neutrino oscillations depend on:
    - **Neutrino energy**



Neutrinos Oscillations

- Neutrino oscillations depend on:
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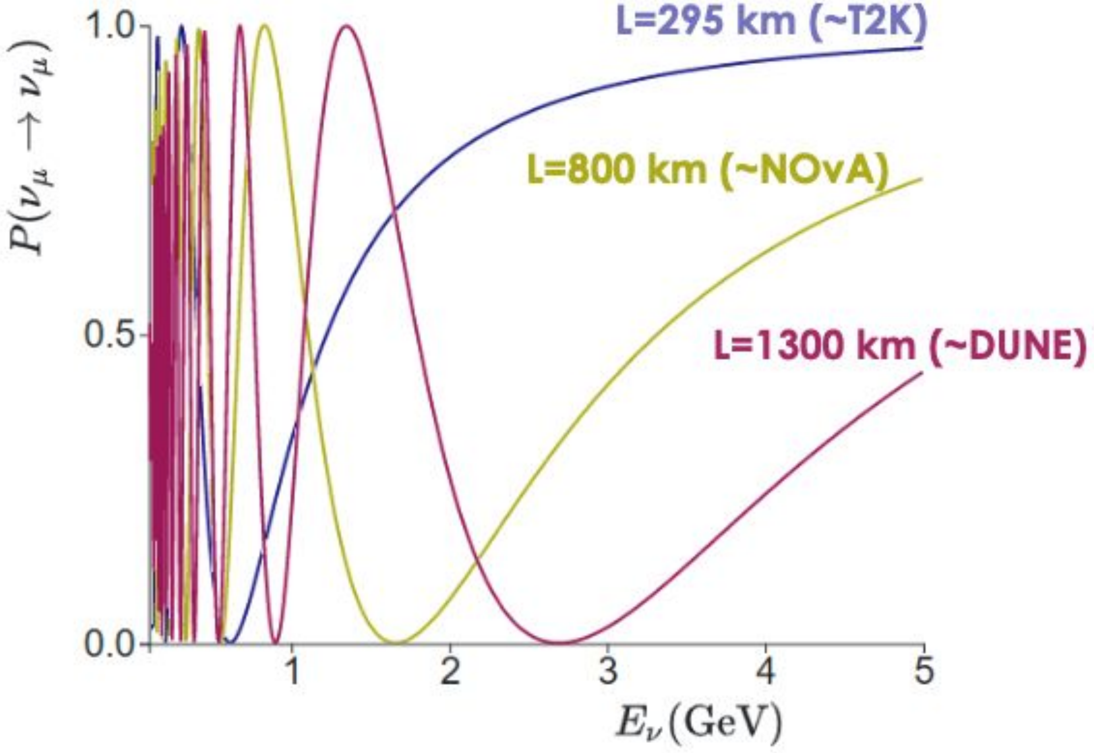
    - **Distance propagated**



Neutrinos Oscillations

- Neutrino oscillations depend on:
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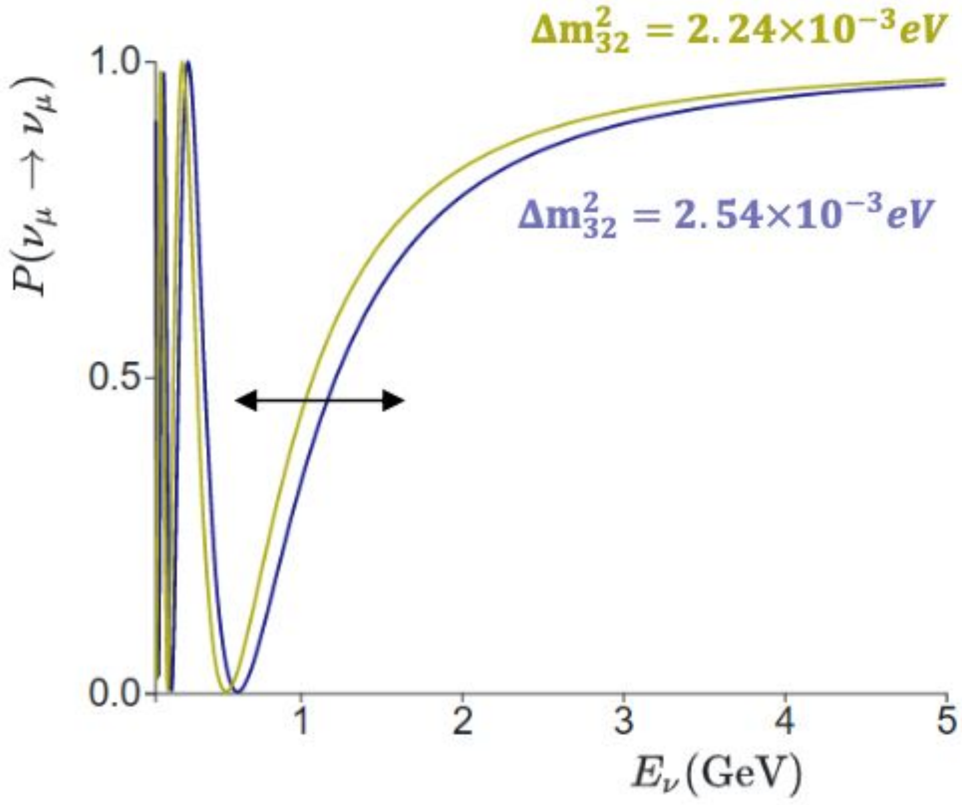
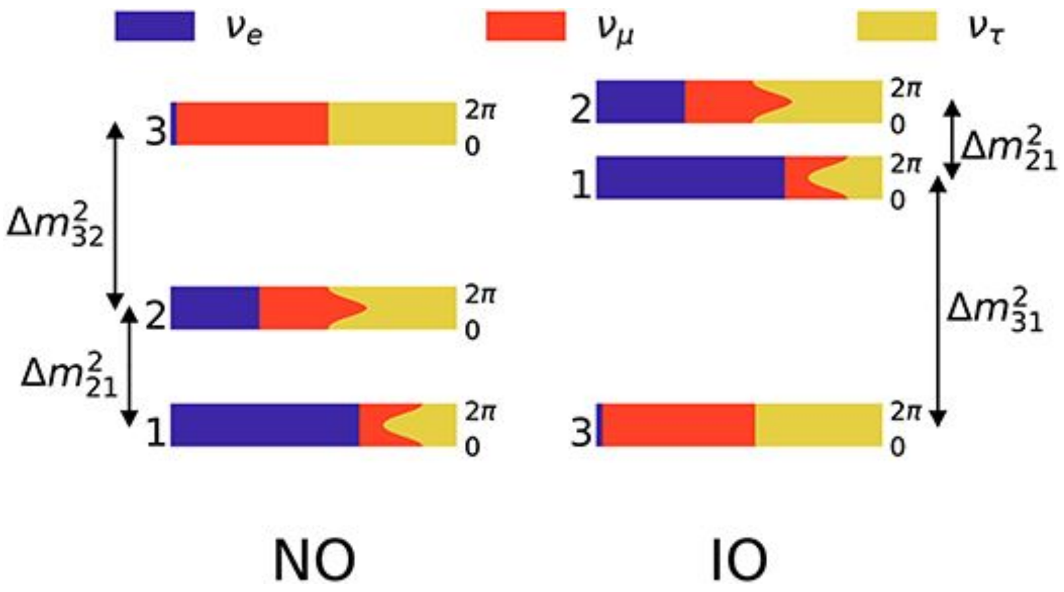
  - **Difference in masses** of ν_1, ν_2, ν_3



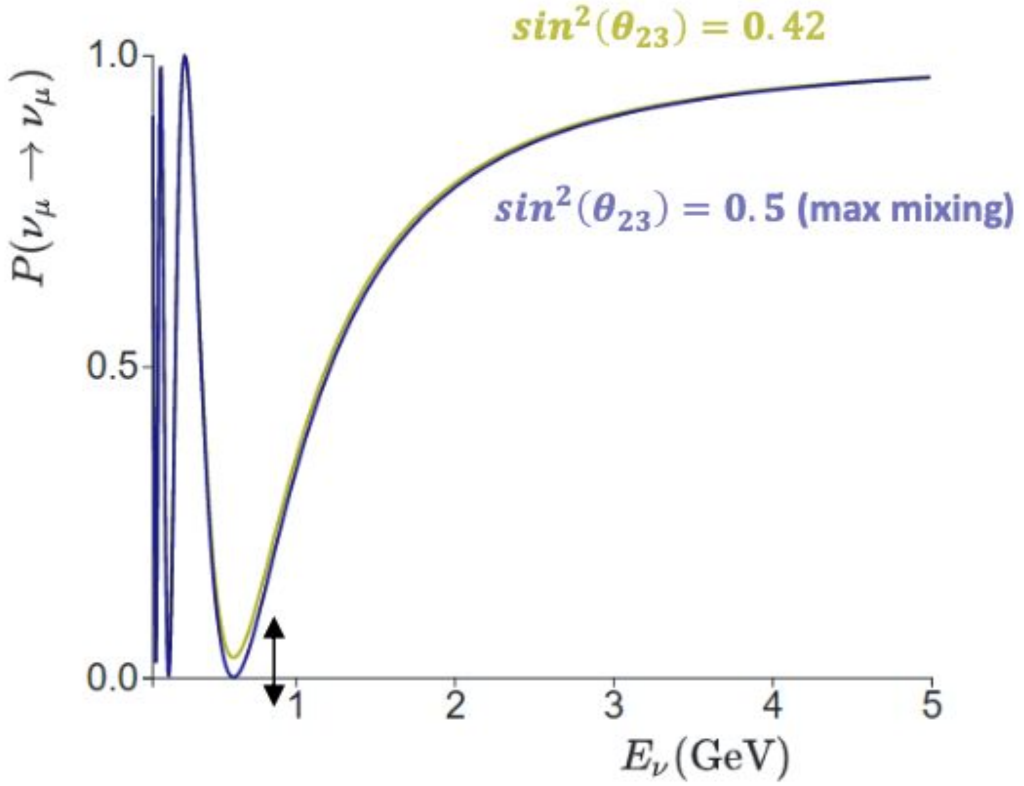


- Currently we don't know the **hierarchy**
  - i.e. **$\Delta m^2_{32} < 0$** or **$\Delta m^2_{32} > 0$**
- In a vacuum there is **no sensitivity** to the sign → we use **matter effects**!

Neutrinos Oscillations

- Neutrino oscillations depend on:
  - **Neutrino energy**
  - **Distance propagated**
  - **Difference in masses** of ν_1, ν_2, ν_3
  - **PMNS mixing parameters**

- **Three** mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric/ Accelerator}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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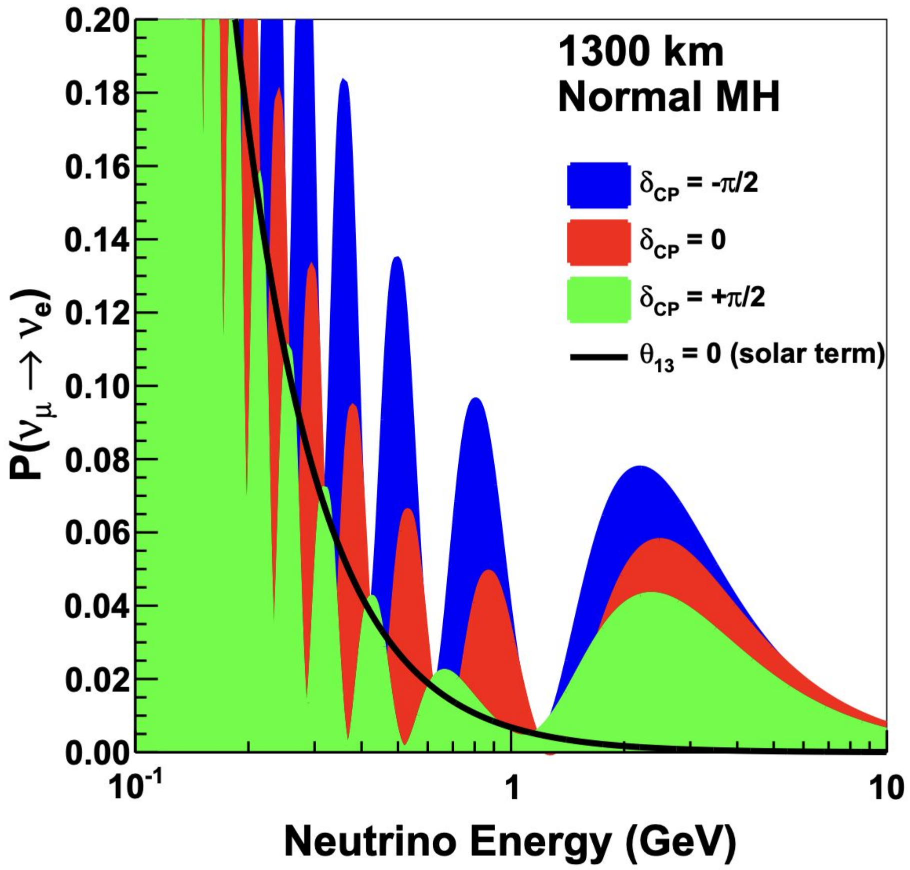

- **Three** mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$
- **One** CP-Violating phase: δ_{CP}

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What do we know?

(F. Capozzi et al., Phys. Rev. D 104, 8, 083031)

- $\sin^2\theta_{23} = 0.455 \pm 0.018$
- $\sin^2\theta_{13} = 0.0223 \pm 0.0007$
- $\sin^2\theta_{12} = 0.303 \pm 0.13$
- $|\Delta m^2_{32}| = (2.45 \pm 0.03) \times 10^{-3}\ \text{eV}^2$
- $\Delta m^2_{21} = (7.36 \pm 0.16) \times 10^{-5}\ \text{eV}^2$

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What don't we know?

- Do neutrinos violate CP?
  - $\delta_{CP} = 1.24 \pm 0.18\ \pi$ rads
- Mass hierarchy?
- $\theta_{23} > 45°$? (**Octant**)
- New Physics
  - PMNS Unitarity / sterile neutrinos?
  - Non standard interactions
  - And more …

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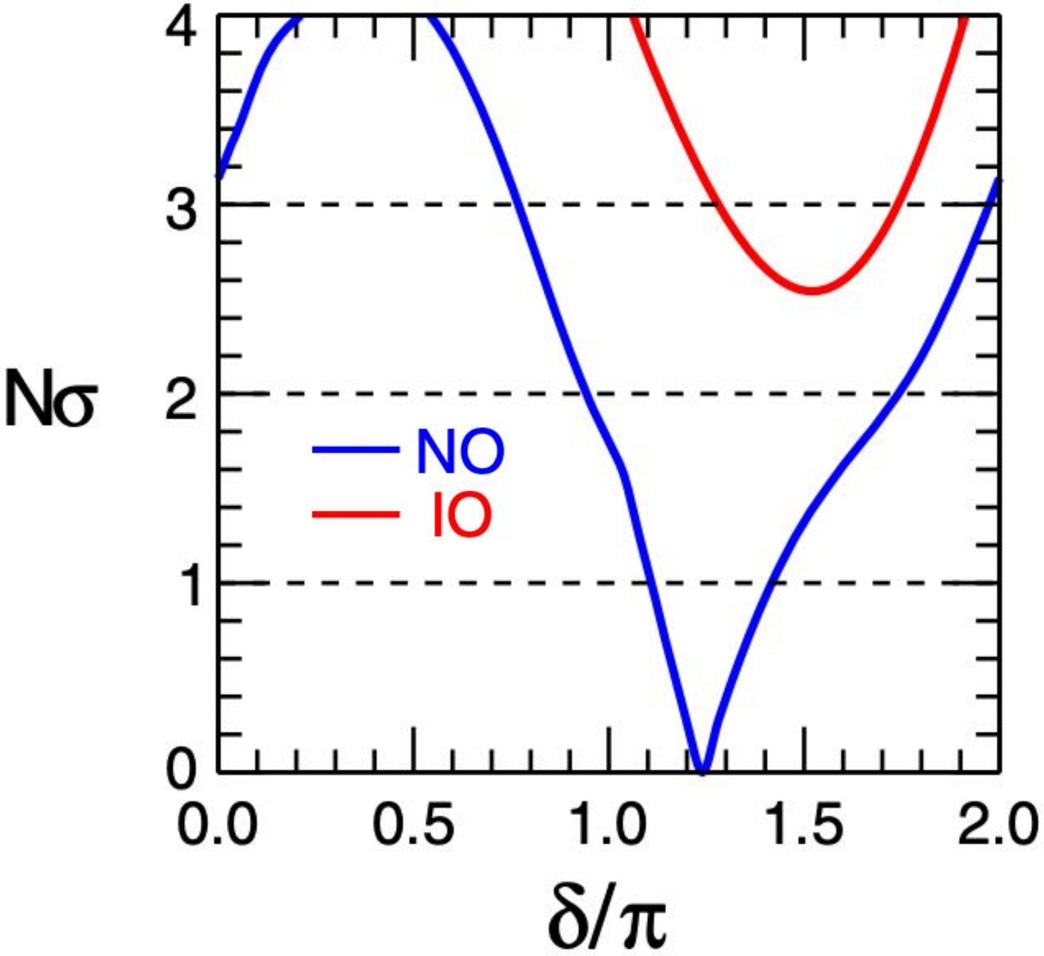

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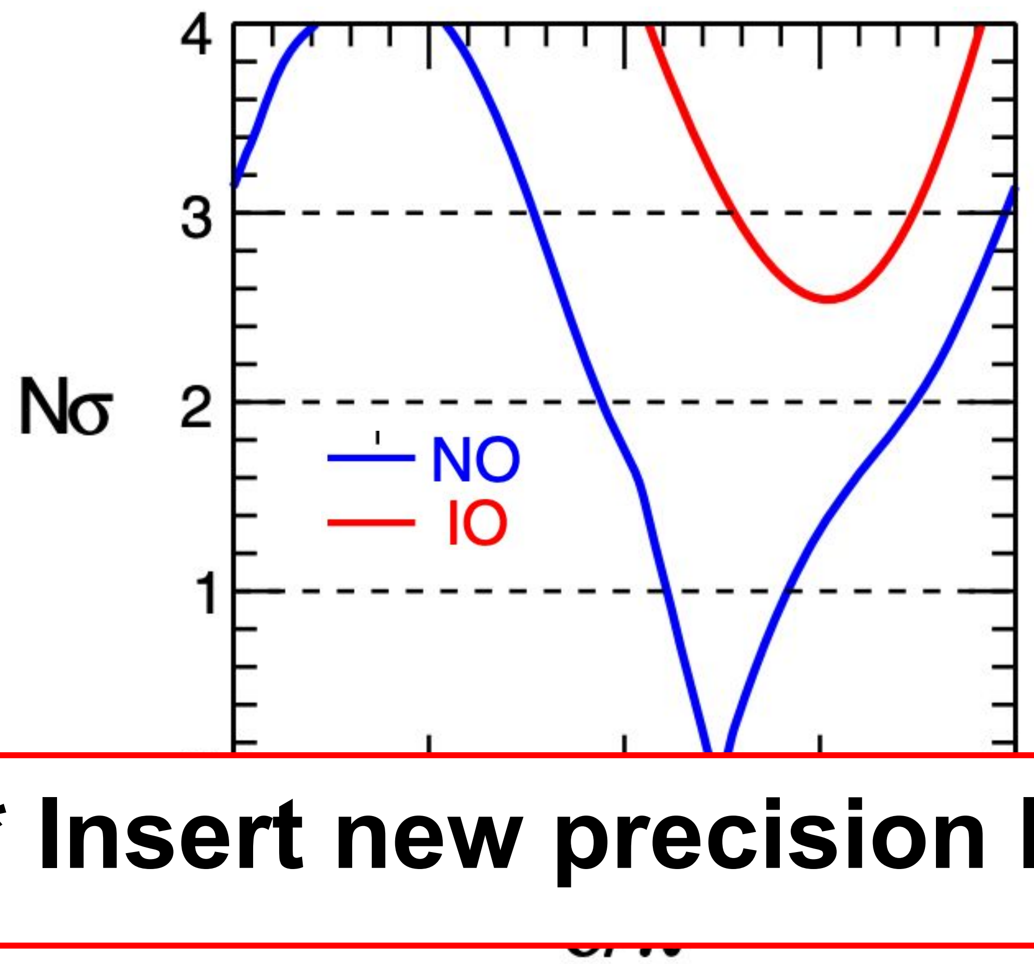

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*** Insert new precision long-baseline experiment here***

The Deep Underground Neutrino Experiment

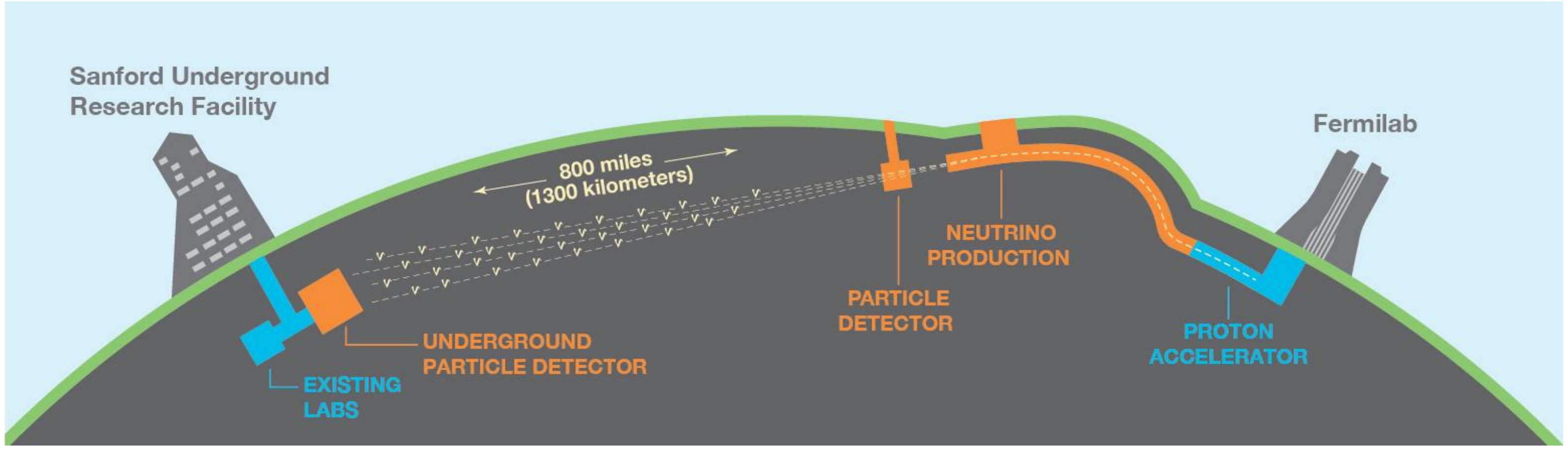
DUNE Collaboration

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



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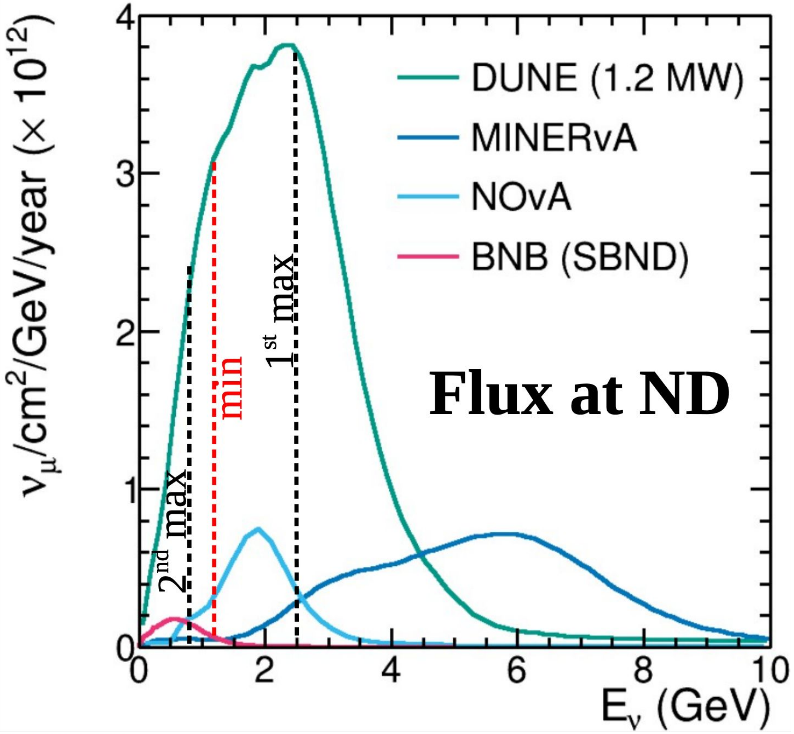
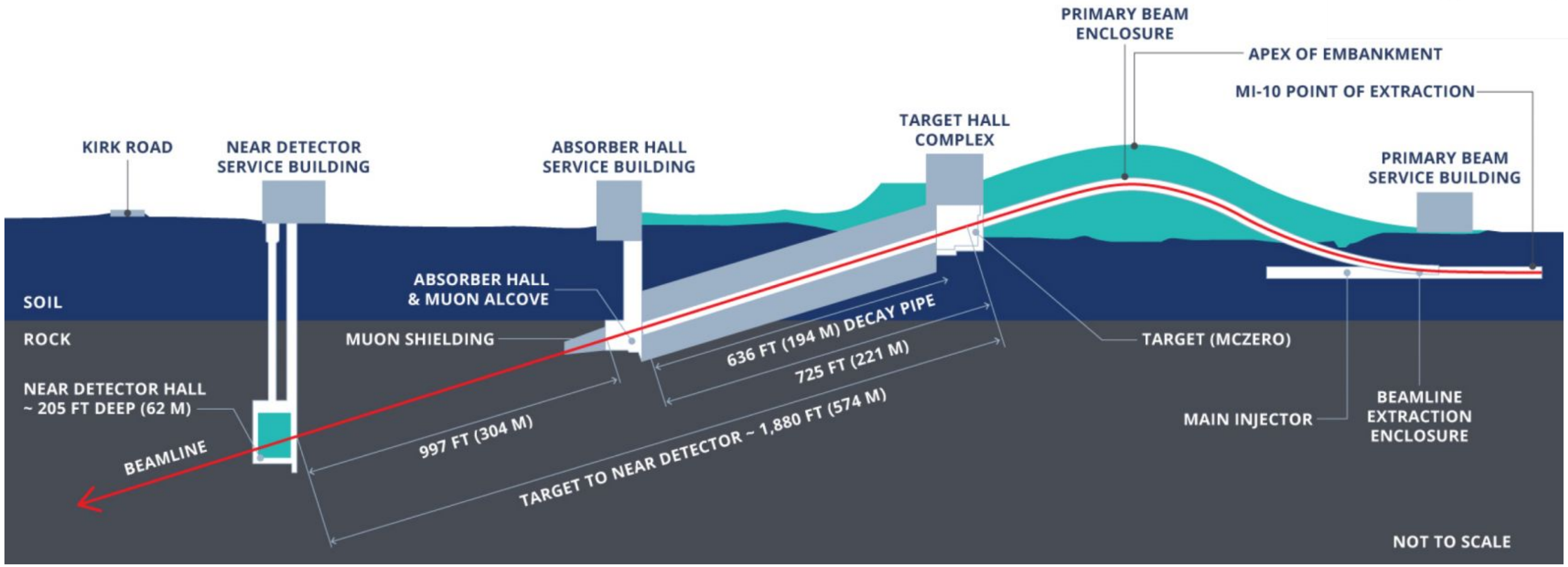
Neutrino beam

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

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



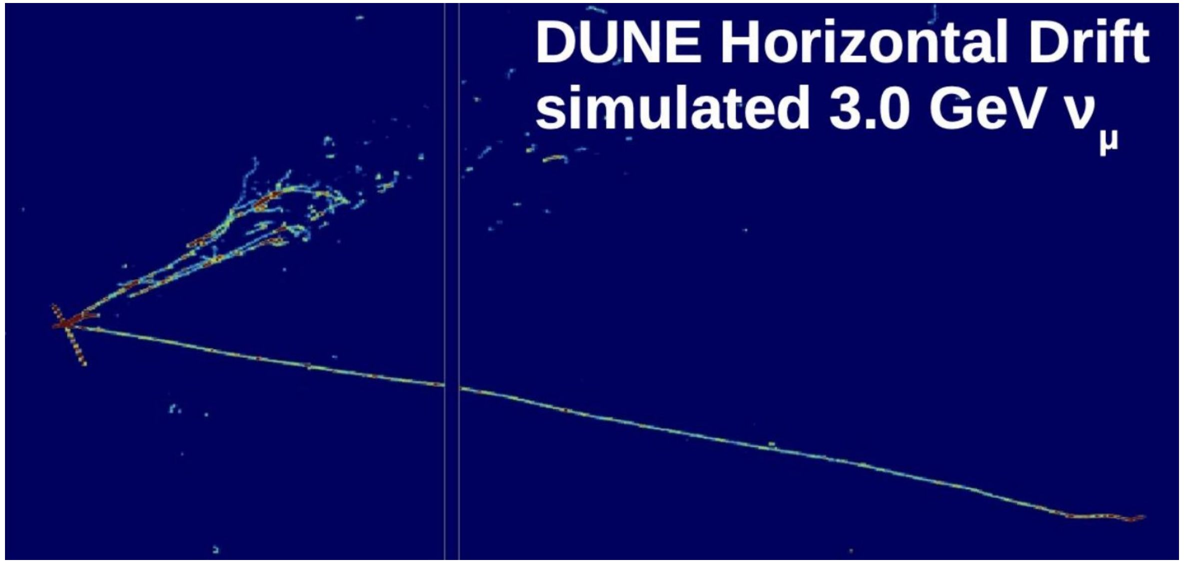


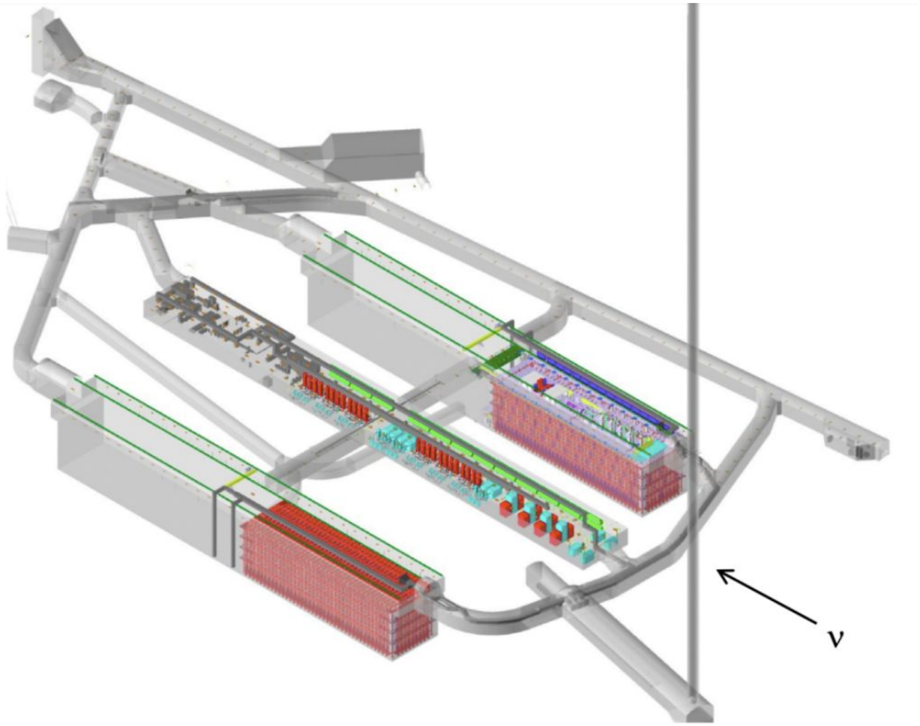
Far detector (FD)

- 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)**

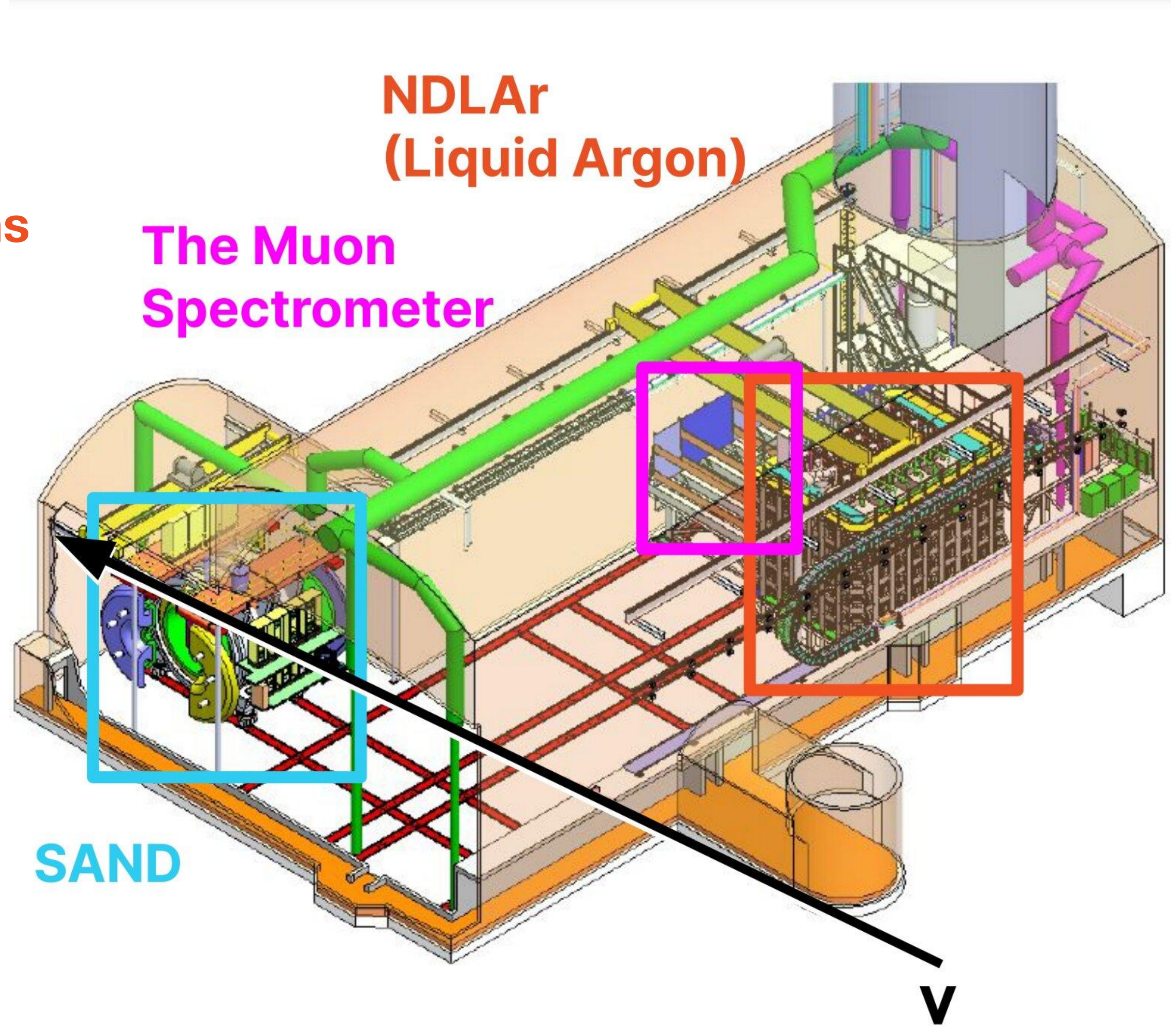
- VD is the baseline design for Module 3 & 4





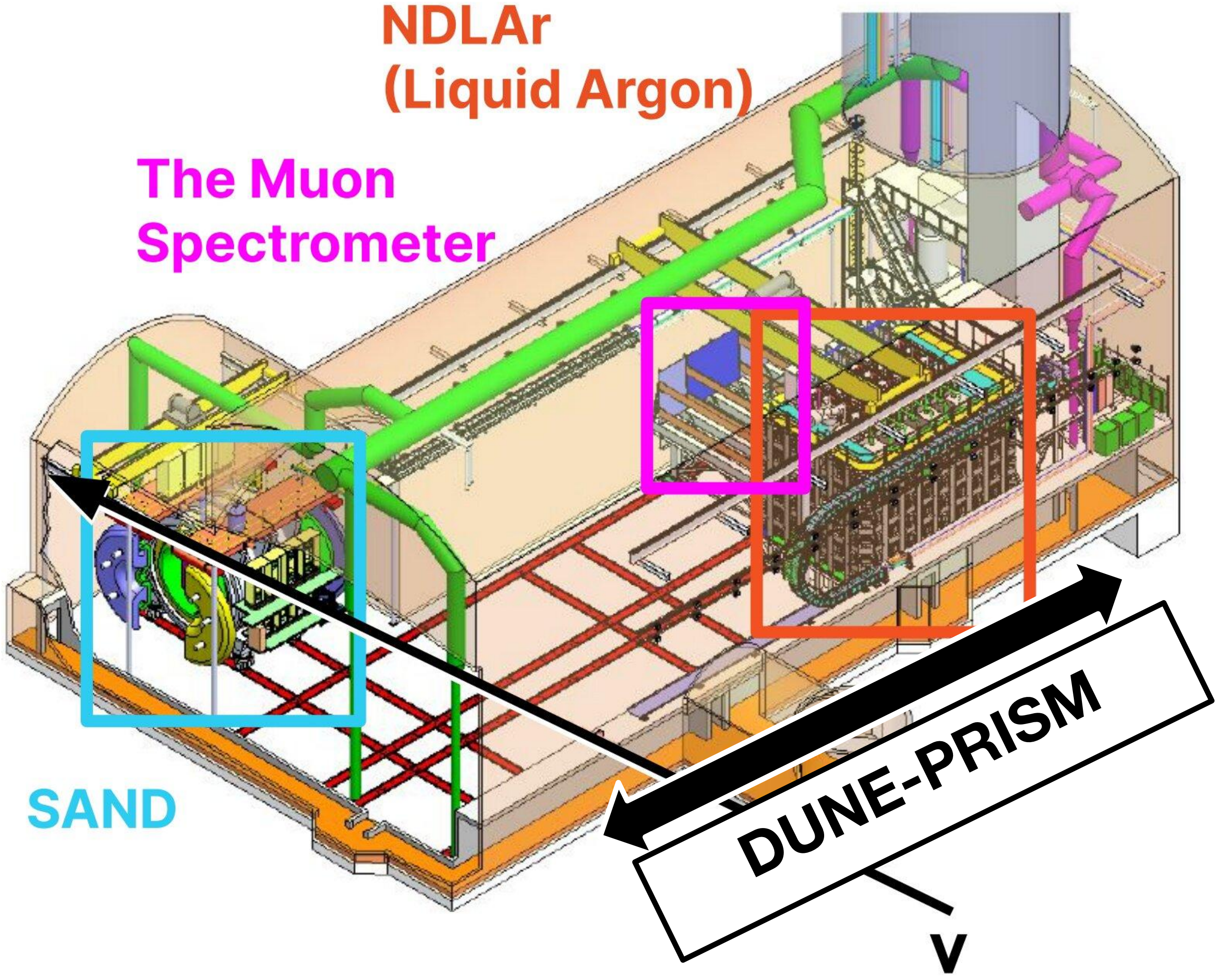
Near detector (ND)

- **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
  - Multiple targets → exclusive neutrino-nucleus measurements



Near detector (ND)

- **DUNE-PRISM:**
  - Use off-axis effect to sample **multiple fluxes** using the same detectors
  - Probe the **smearing** between **observed and true energy**



Inferring Oscillation Parameters

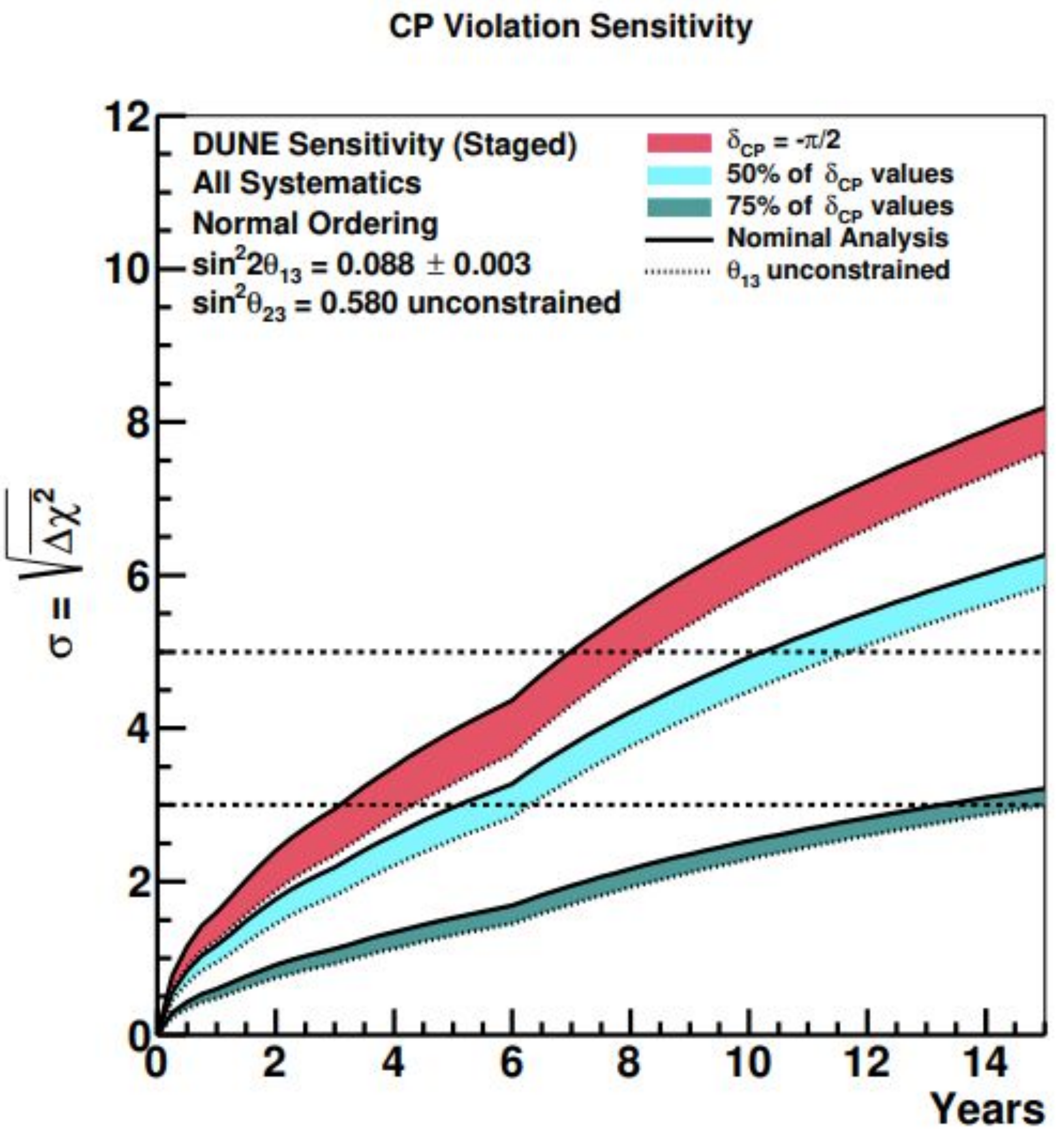
How do long-baseline analyses work?

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

- 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**

2020 Sensitivity Study

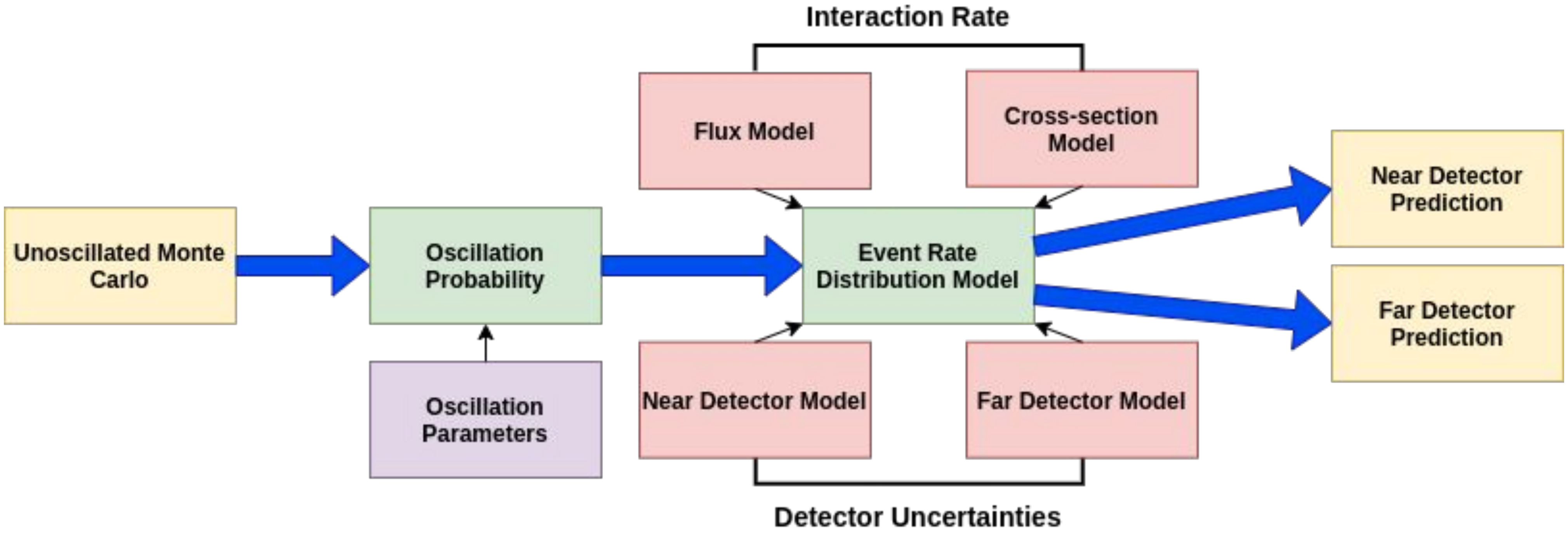
- Current DUNE sensitivities produced using **frequentist framework**
- **Full results available** in "Long-baseline neutrino oscillation physics potential of the DUNE experiment" – Eur. Phys. J. C 80, 978 (2020)
- Sensitivity to **CP violation** depends on the "**true" value** of $\boldsymbol{\delta_{CP}}$
  - What percentage of true values of $\boldsymbol{\delta_{CP}}$ can we exclude CP conservation to … sigma



Bayesian Study

Analysis Strategy

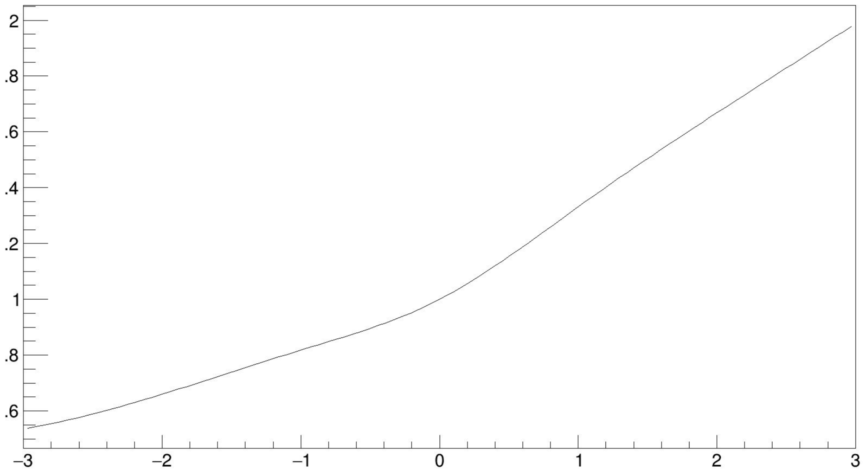
- **Oscillation** probabilities, **flux** model, **interaction** model and **detector** model → **predictions** of **far and near detector spectra**
- Build **likelihood space** as a function of **oscillation** and **systematic** parameters
- **MCMC** to explore the full likelihood space
- **Bayesian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



Systematic Implementation

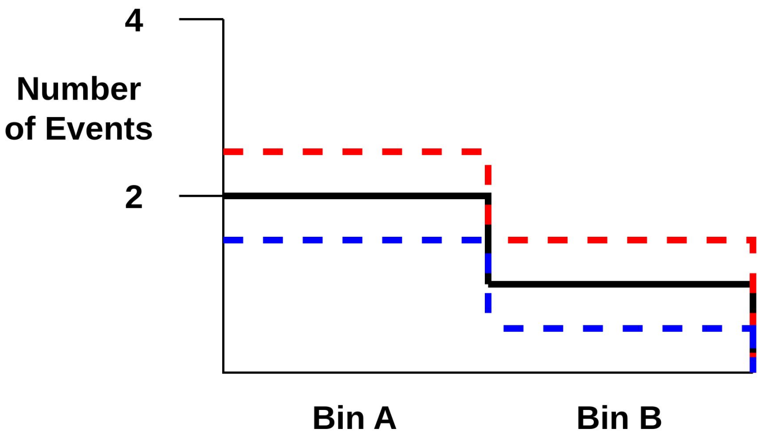
- **High statistics** in next-generation near detectors requires **sophisticated** systematic implementation

Splines



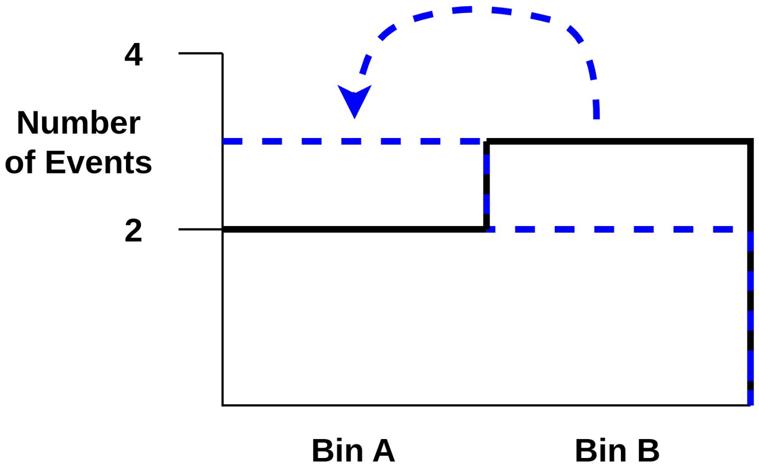
- Continuous response functions using piecewise cubic interpolation
- Binned or **event-by-event**
- Cross-section parameters

Normalisation



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

Shift-like

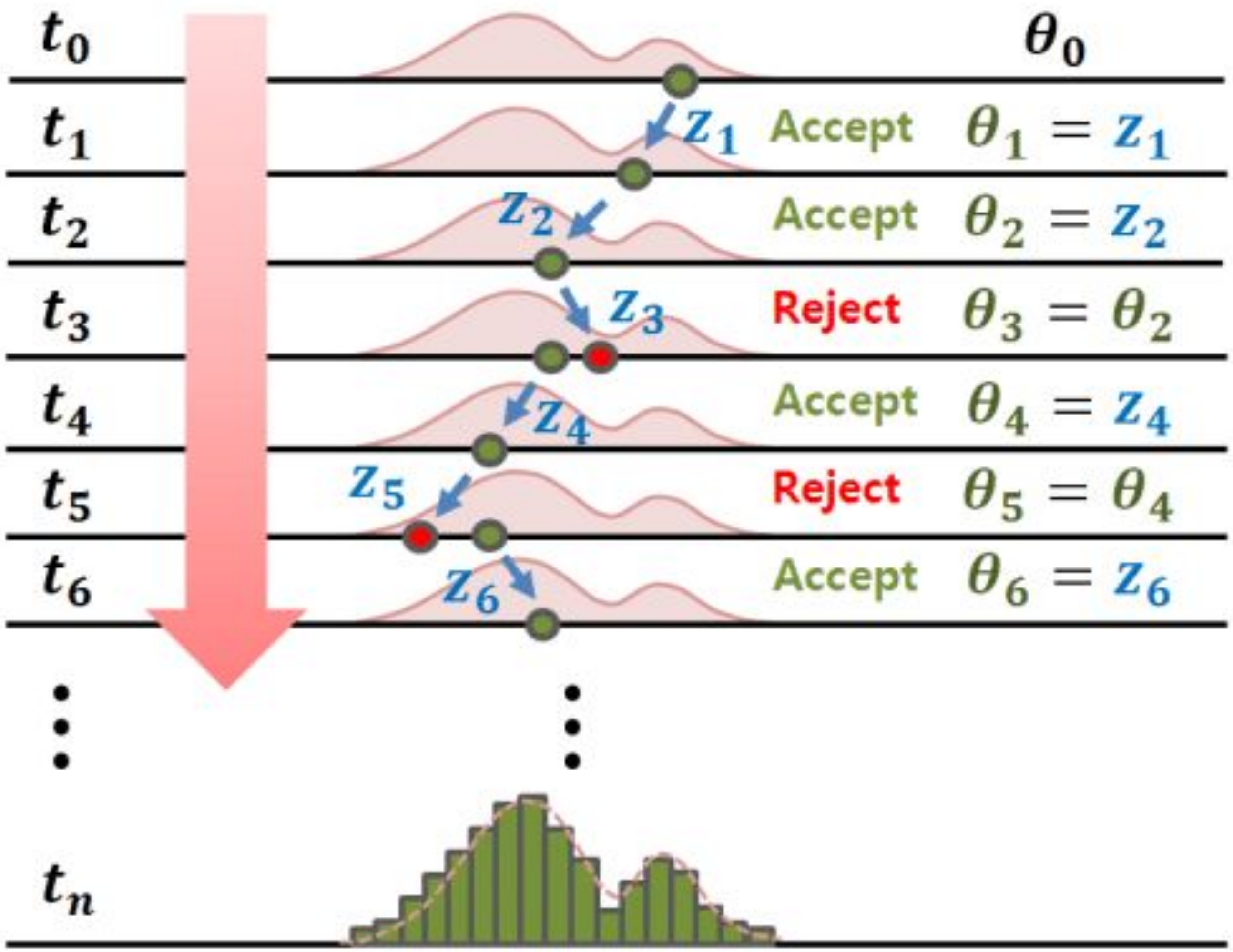


- Move events from one bin to another
- Systematics which **change reconstructed variables**
- Generally for detector systematics

- Events that move bin keep their original weights—> **re-calculate the response for that bin**

MCMC - Markov Chain Monte Carlo

- Semi-random walk around the **full** parameter space
- MR^2T^2 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)

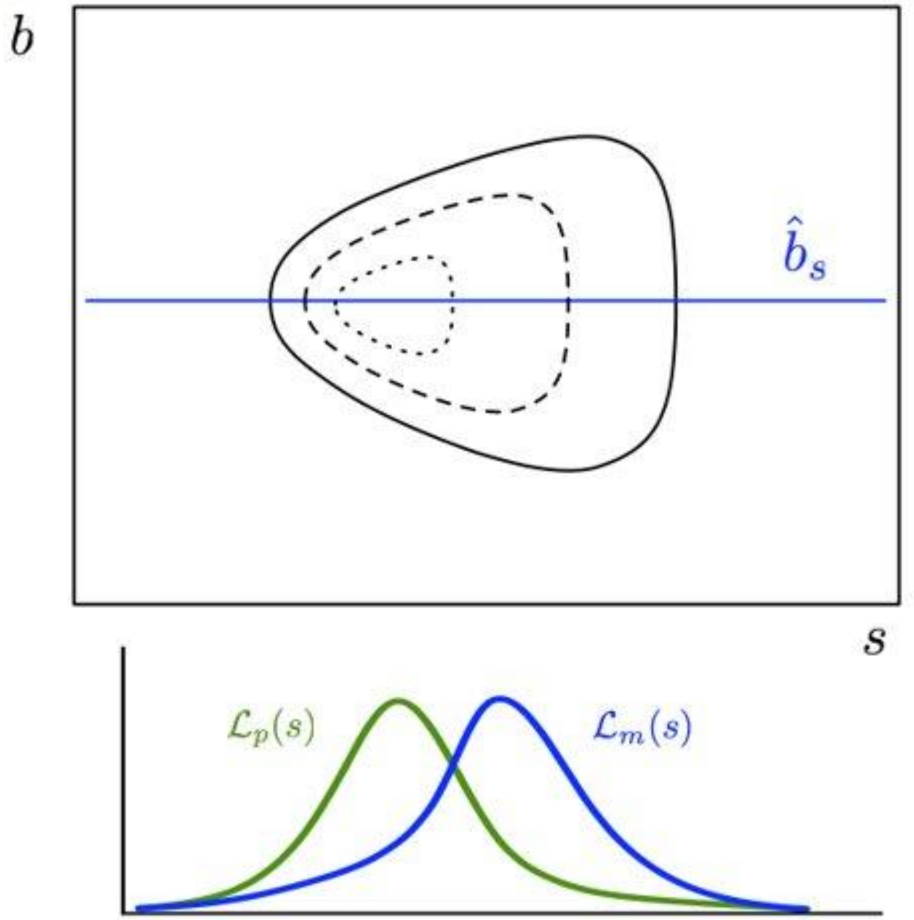


Bayesian Inference

- 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**

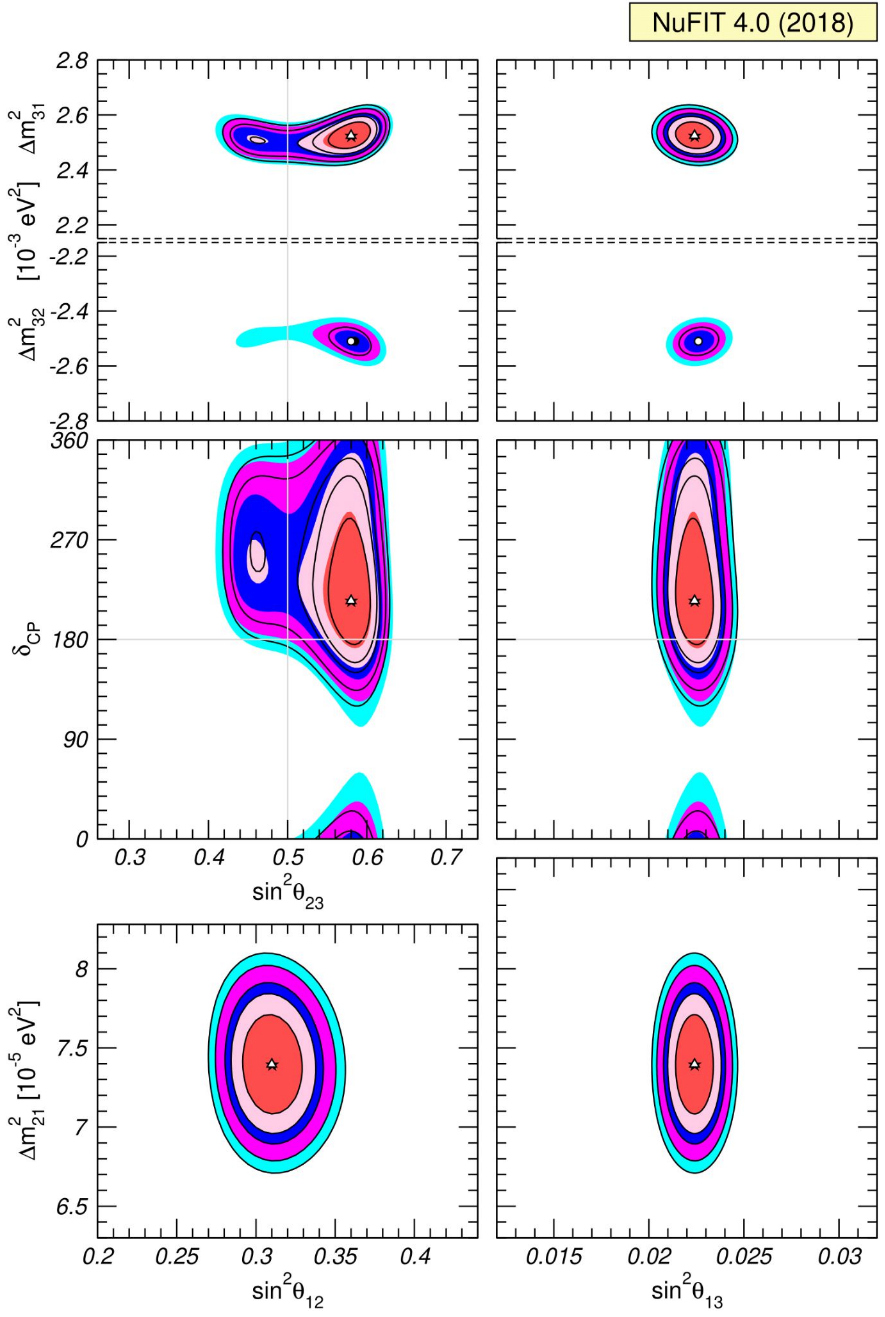
Bayes' theorem:

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



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 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)**



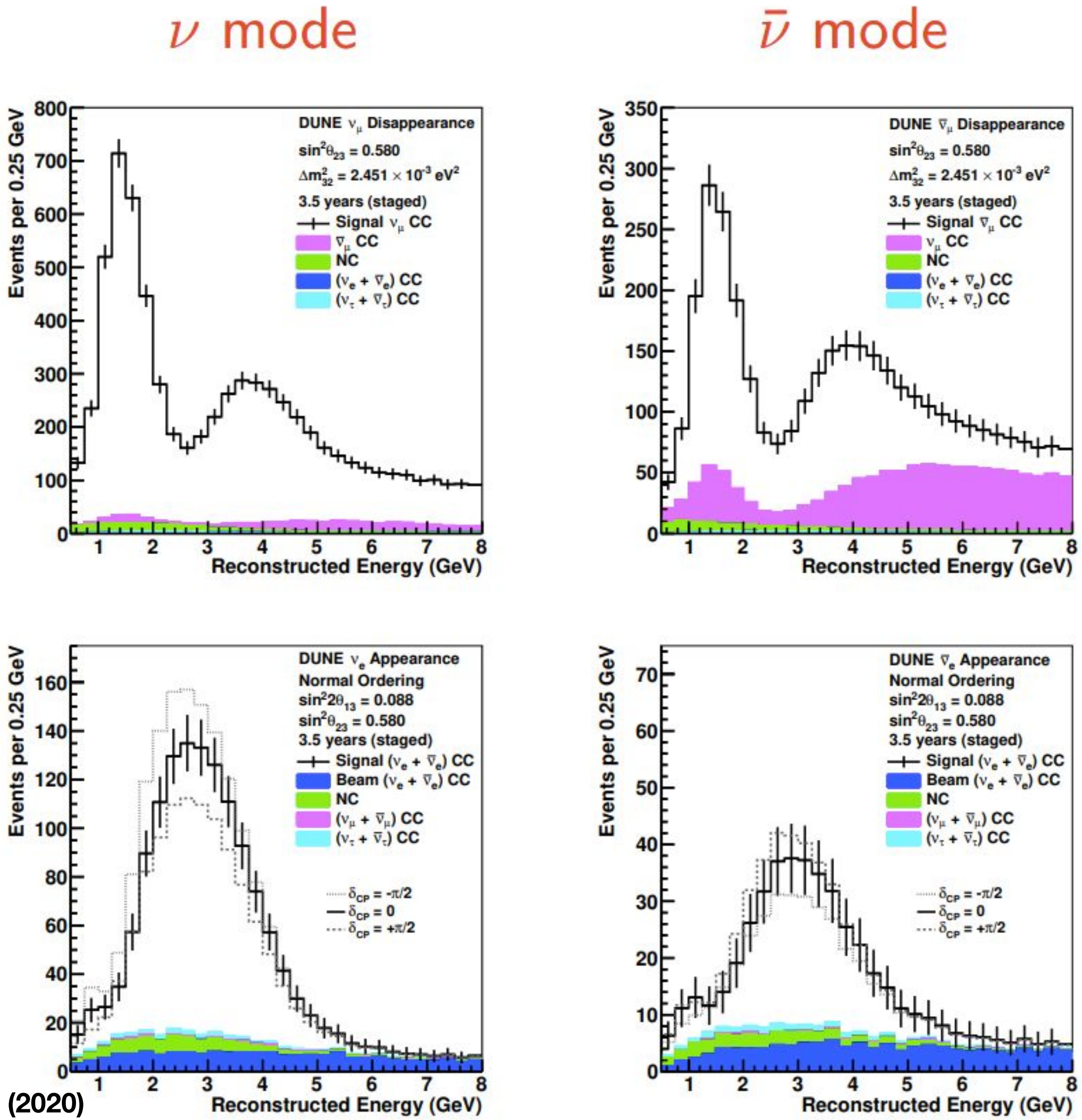
Samples

- 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)

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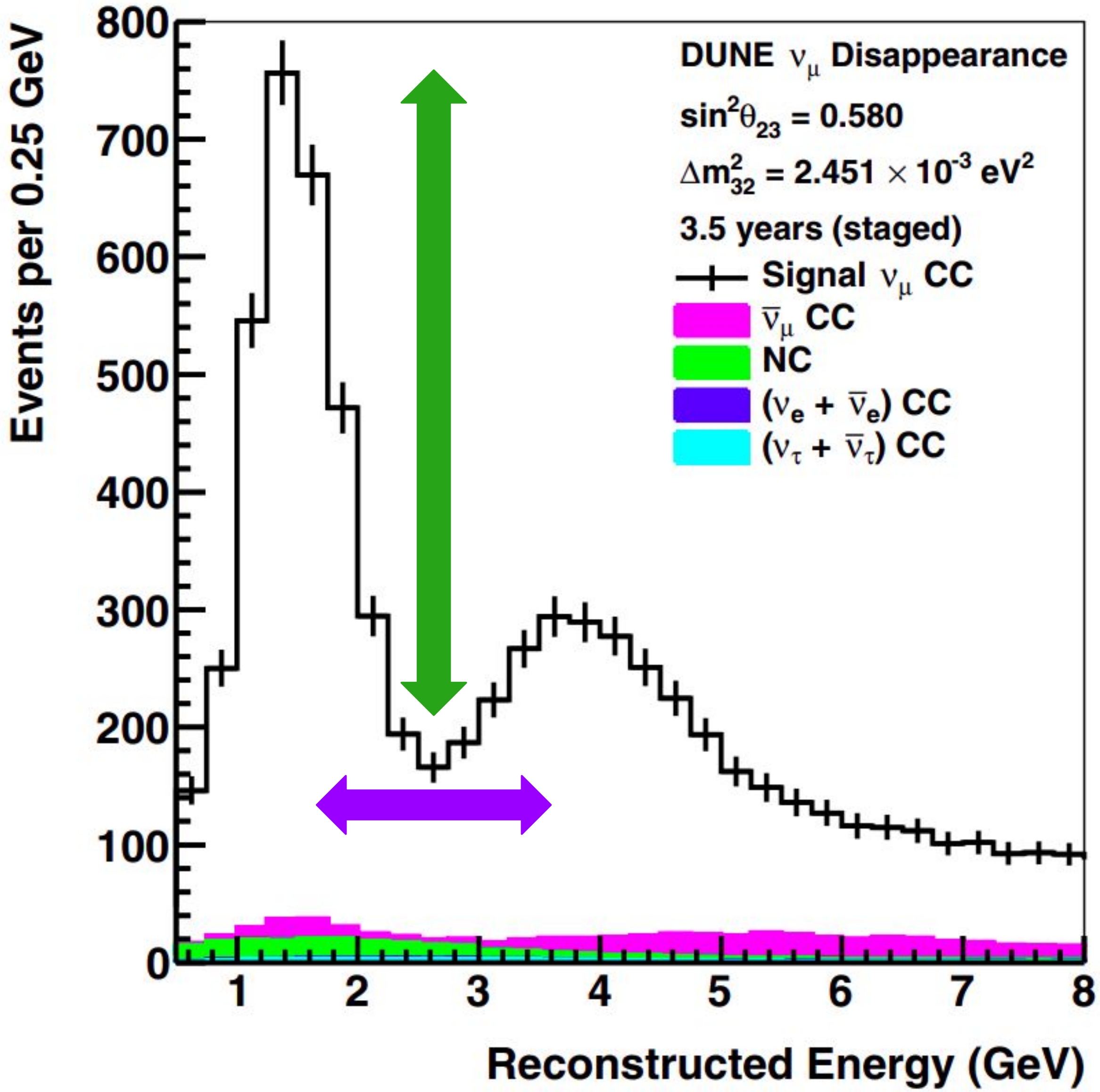

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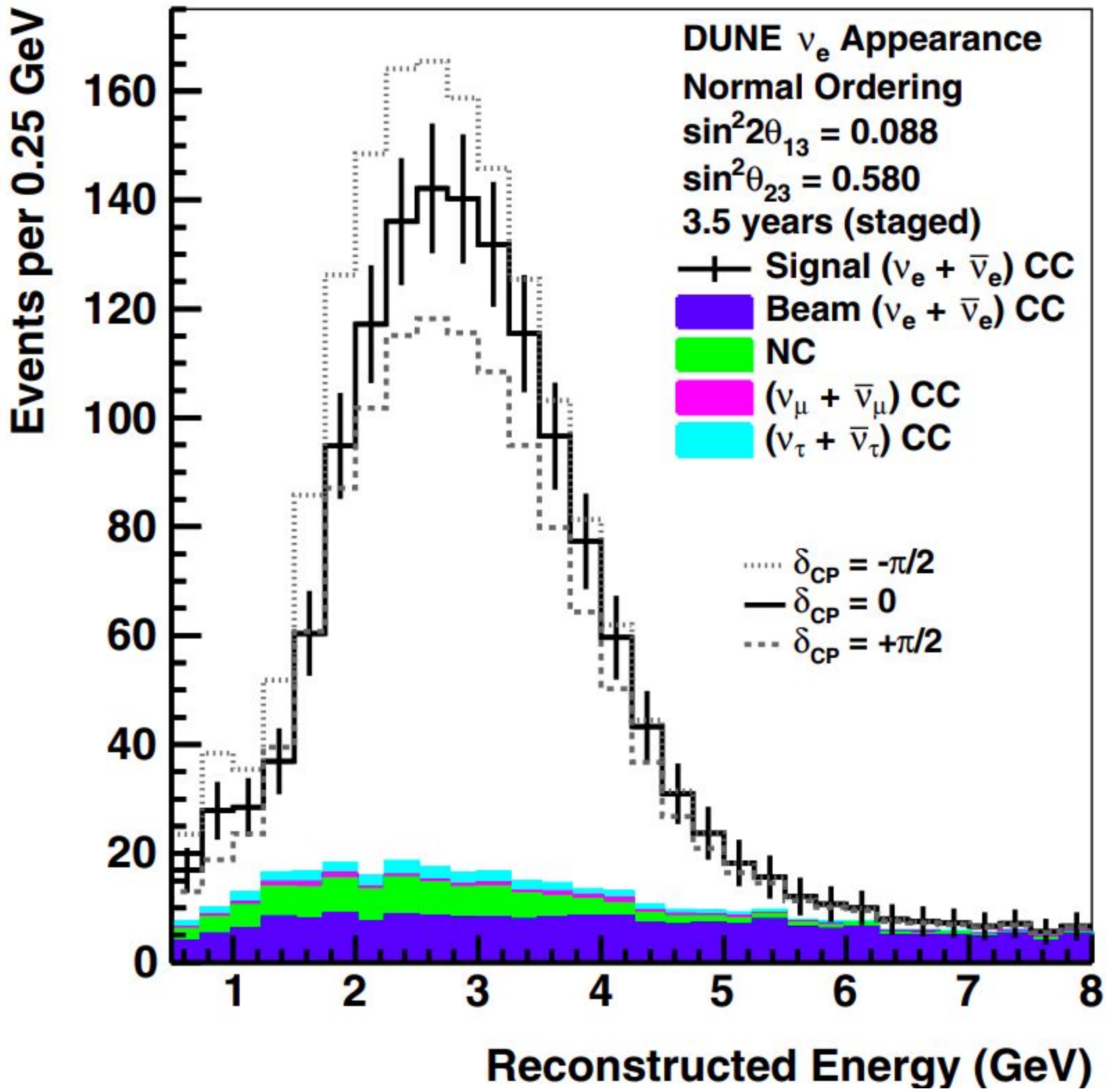

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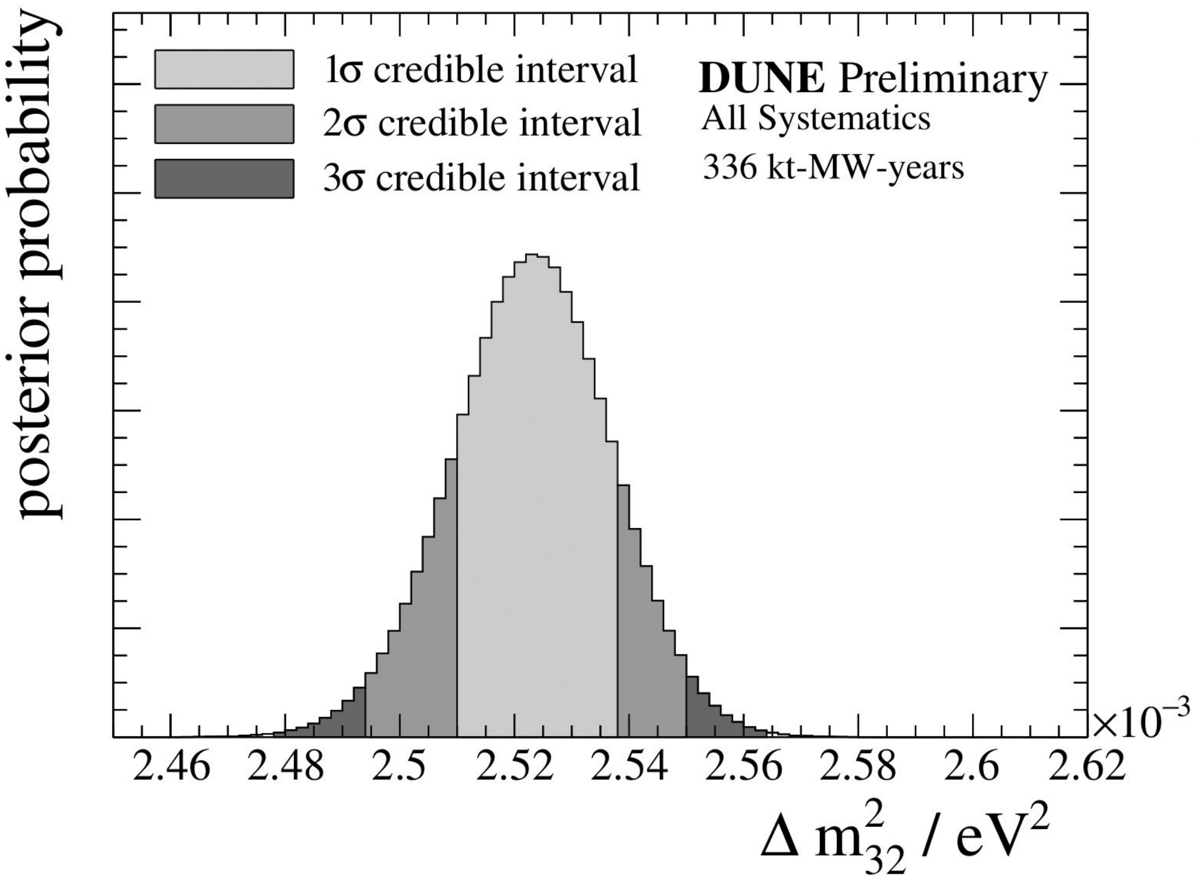
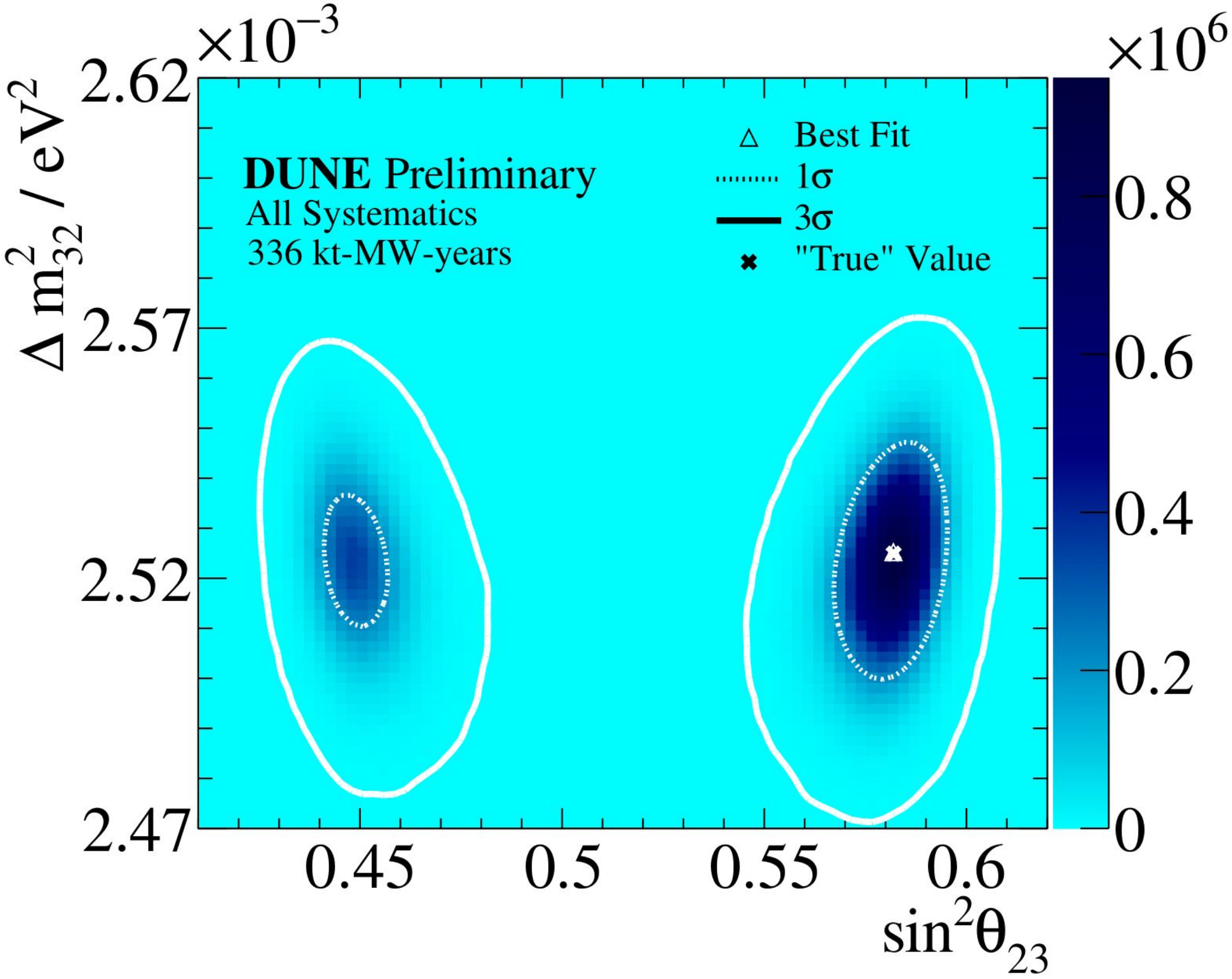
Sensitivities

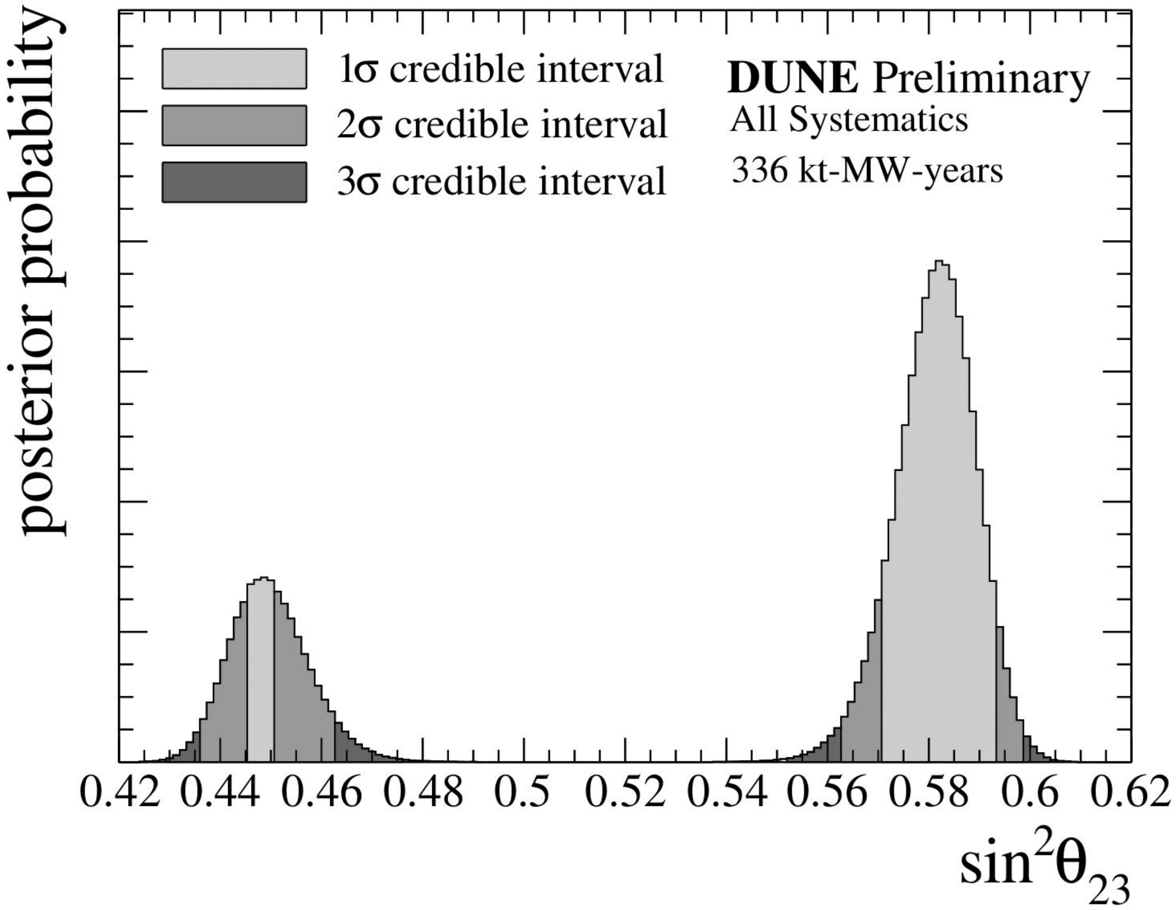
Δm^2_{32} Sensitivity

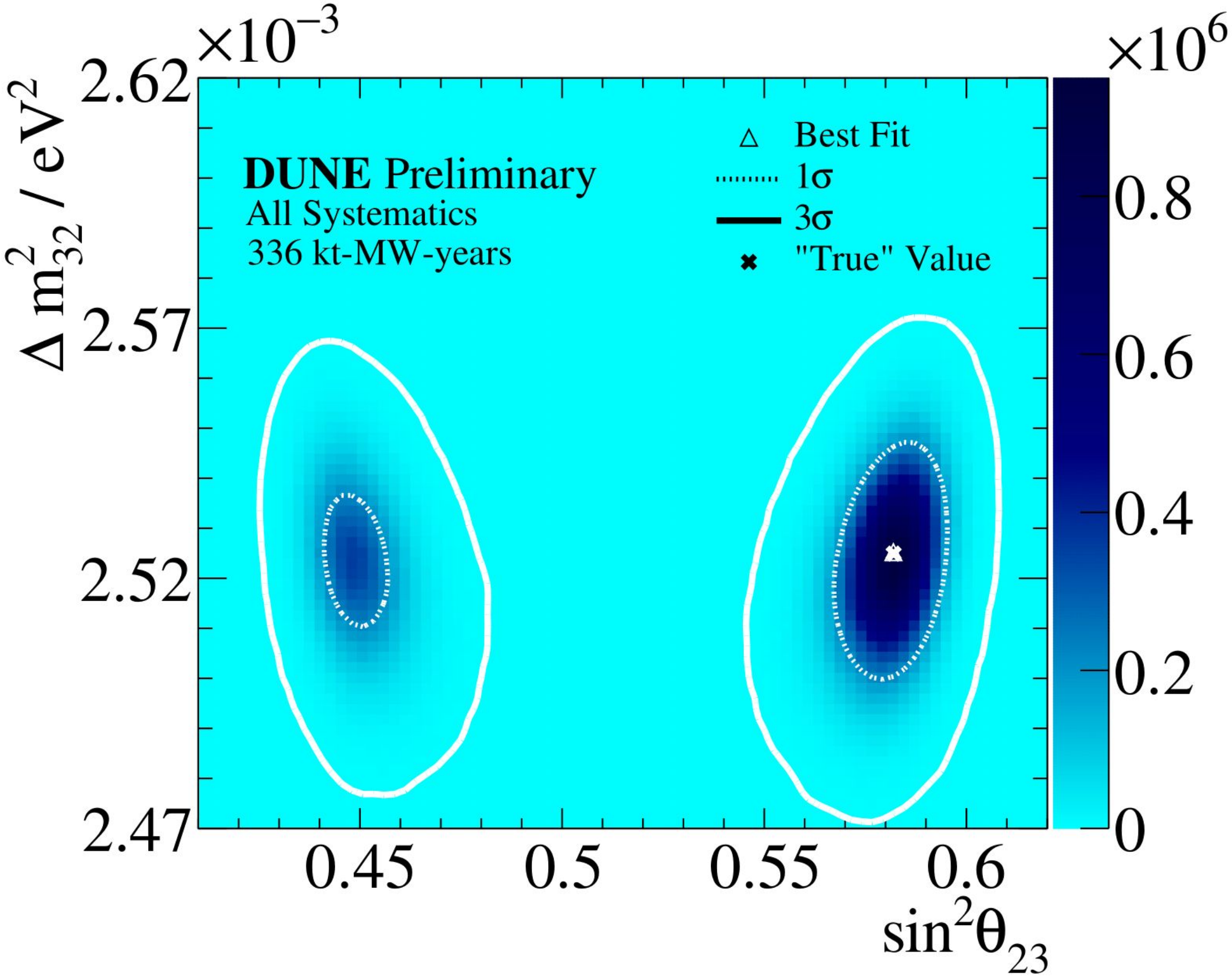




- ***No* posterior in IO → strong sensitivity to the mass hierarchy**
- New **proposal function** for switching hierarchy?

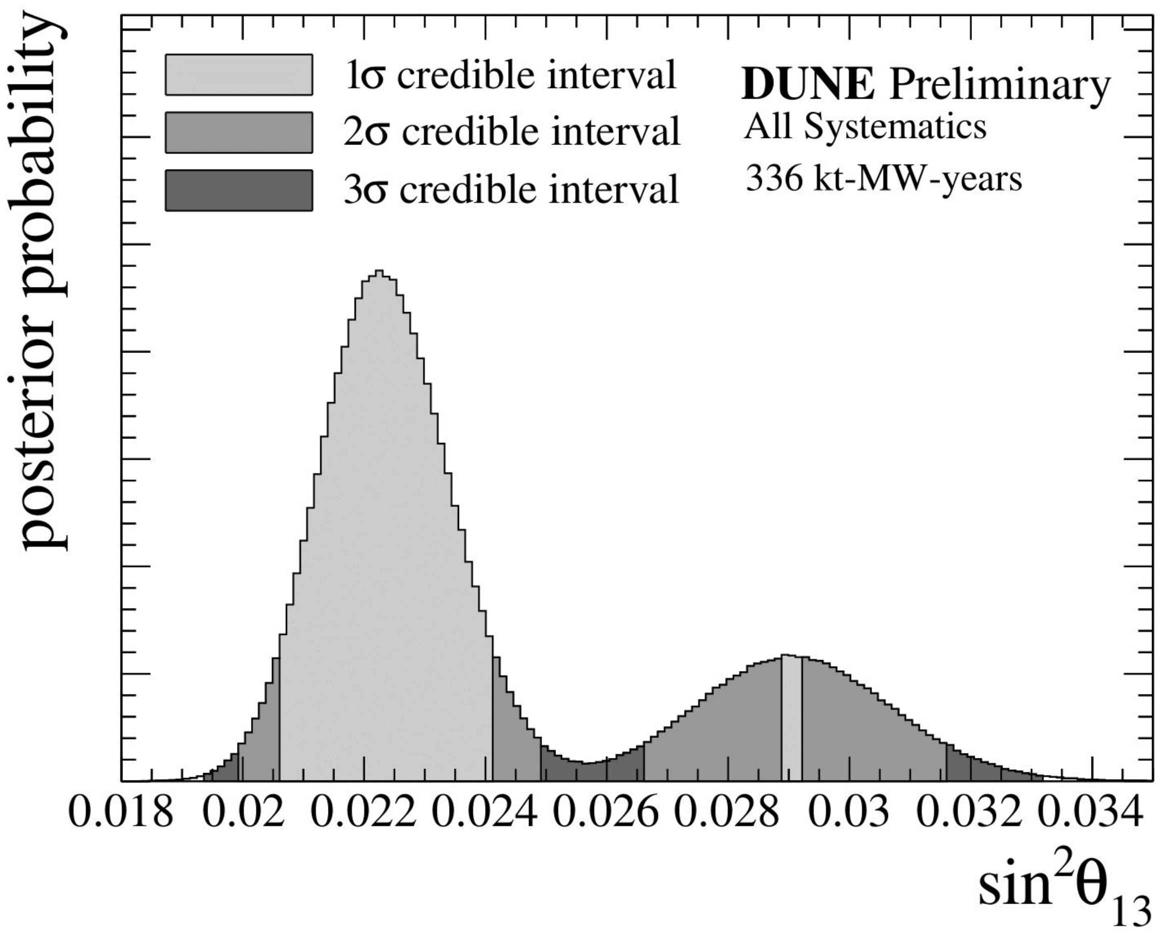
θ_{23} Sensitivity

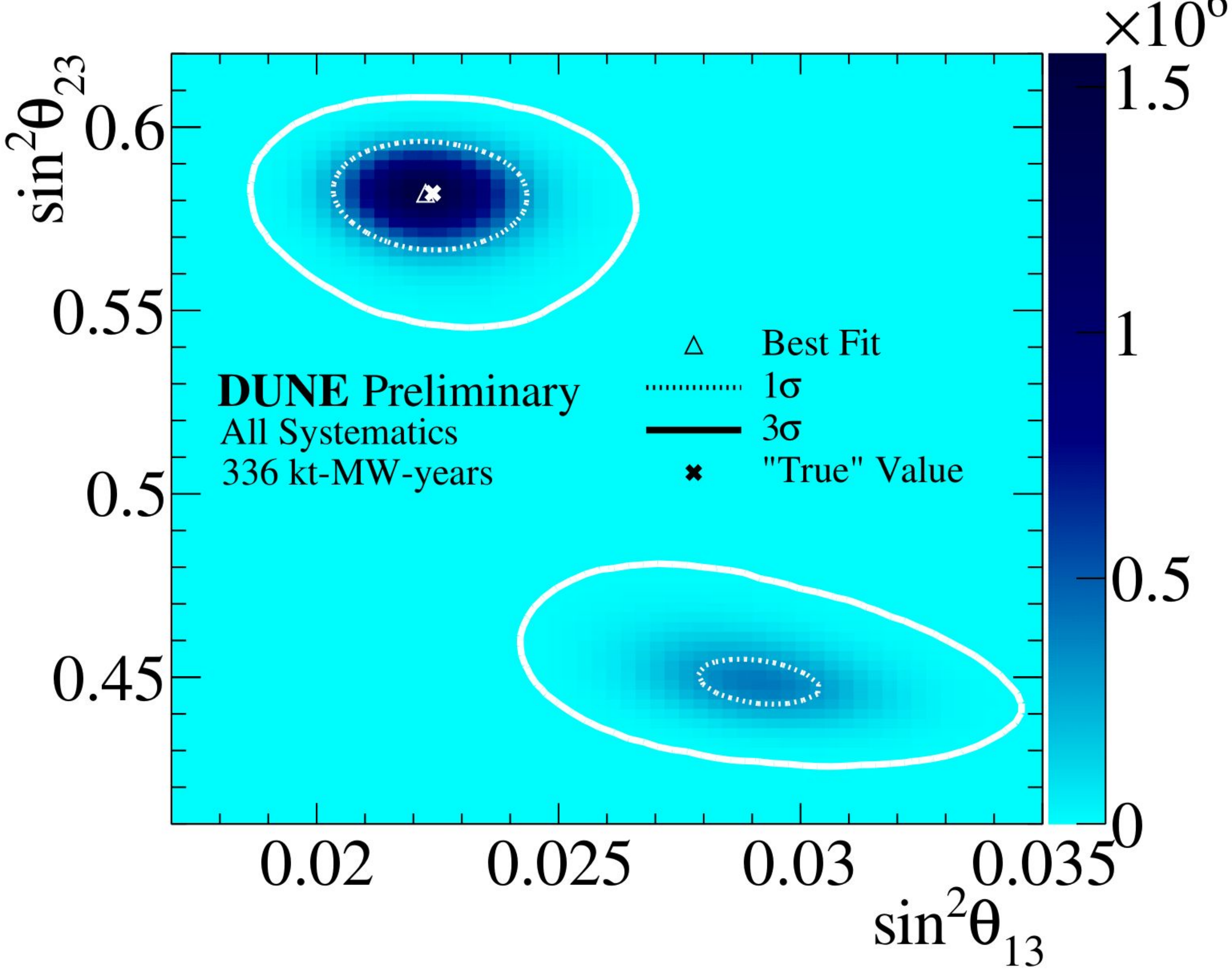




- Both θ_{23} octants being evaluated → **correct octant chosen**
- **Bayes factor of 2.76 → light evidence** for upper octant

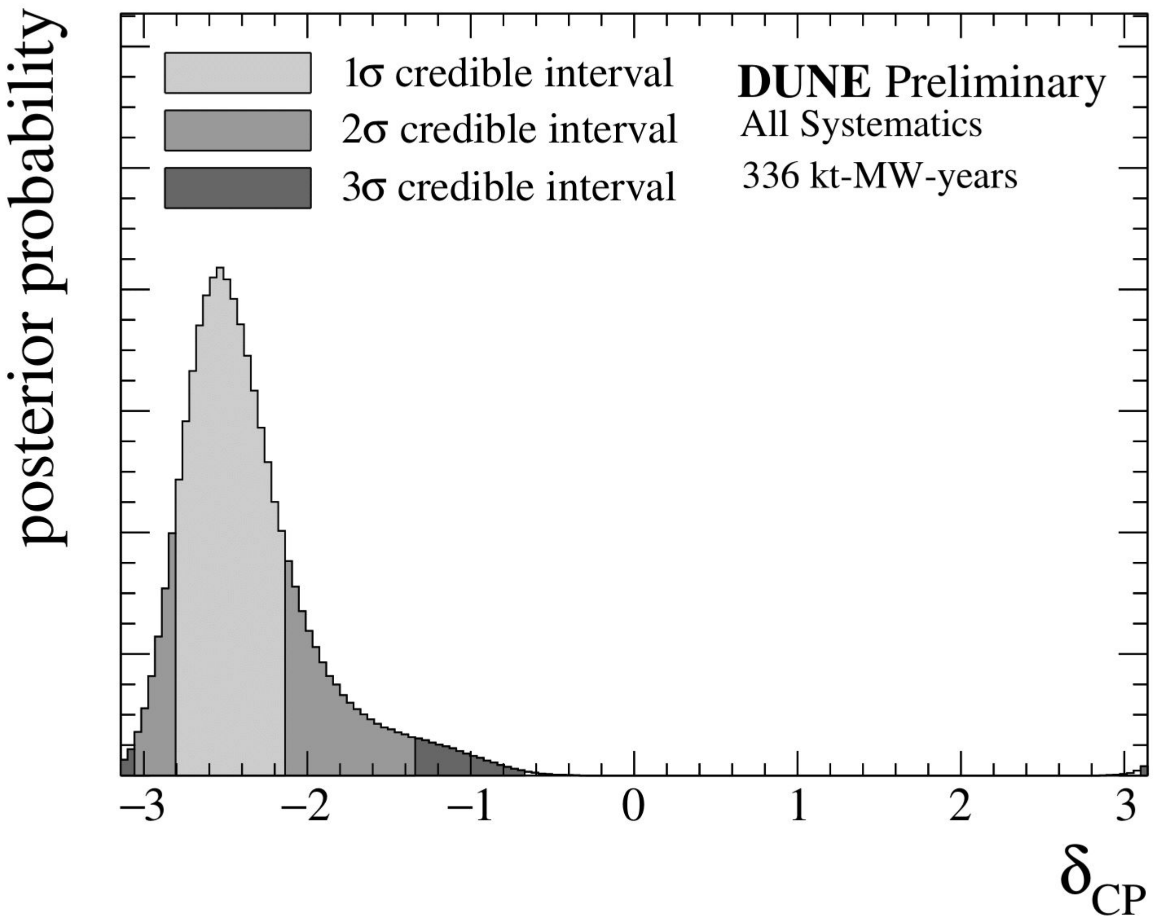
θ_{13} Sensitivity

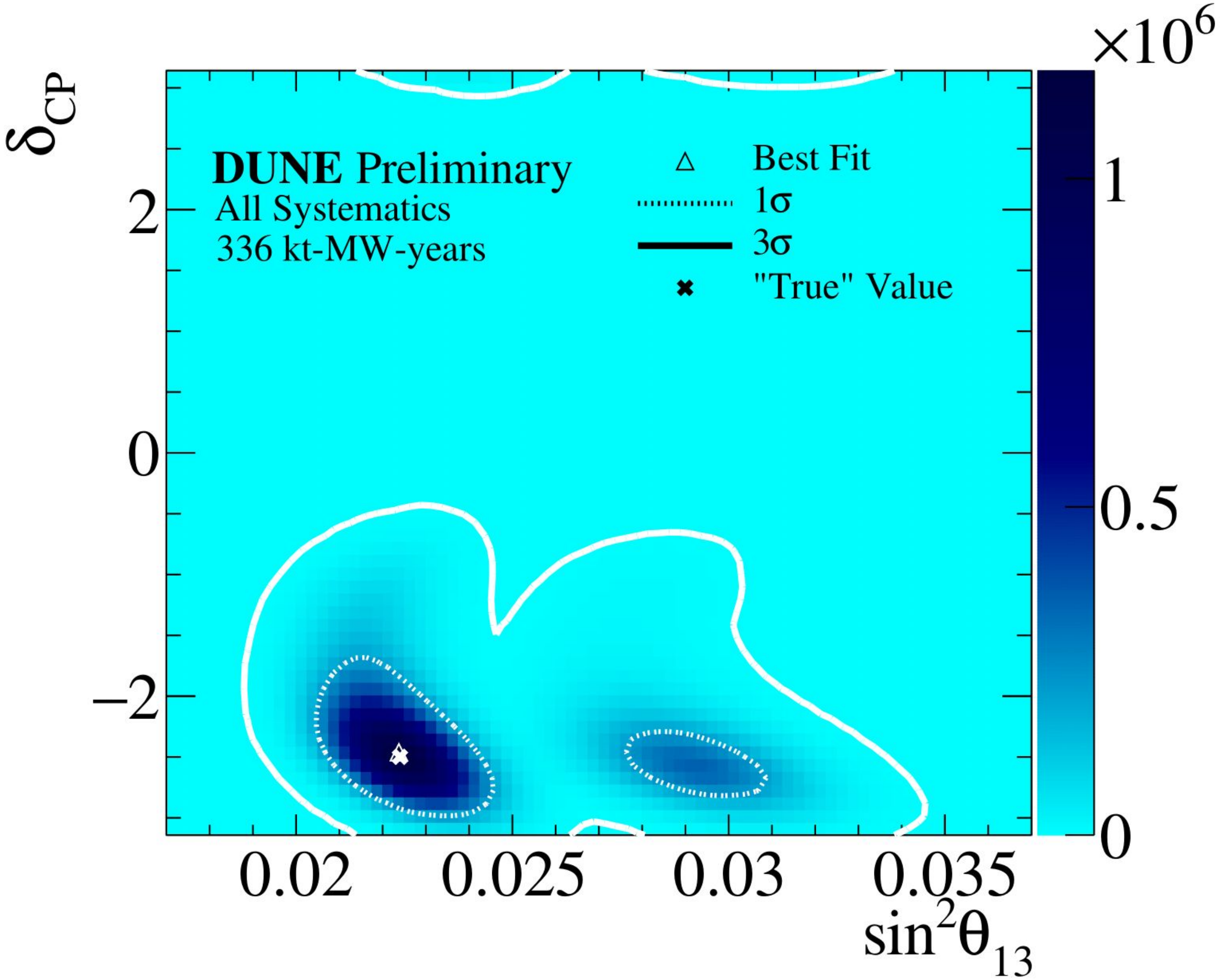




- **Second peak** at larger $\sin^2(\theta_{13})$ values
- Some degeneracy in θ_{13} → as a result of θ_{23} octant degeneracy

δ_{CP} Sensitivity





- **3σ interval** does not include **δ_{CP} = 0**
- Tail towards 0 caused by **δ_{CP}** octant degeneracy → mostly sensitive to **$\sin\delta_{CP}$**

Advantages: 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
  - New result/sensitivity from another experiment?
  - **Does not require a new fit!**

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

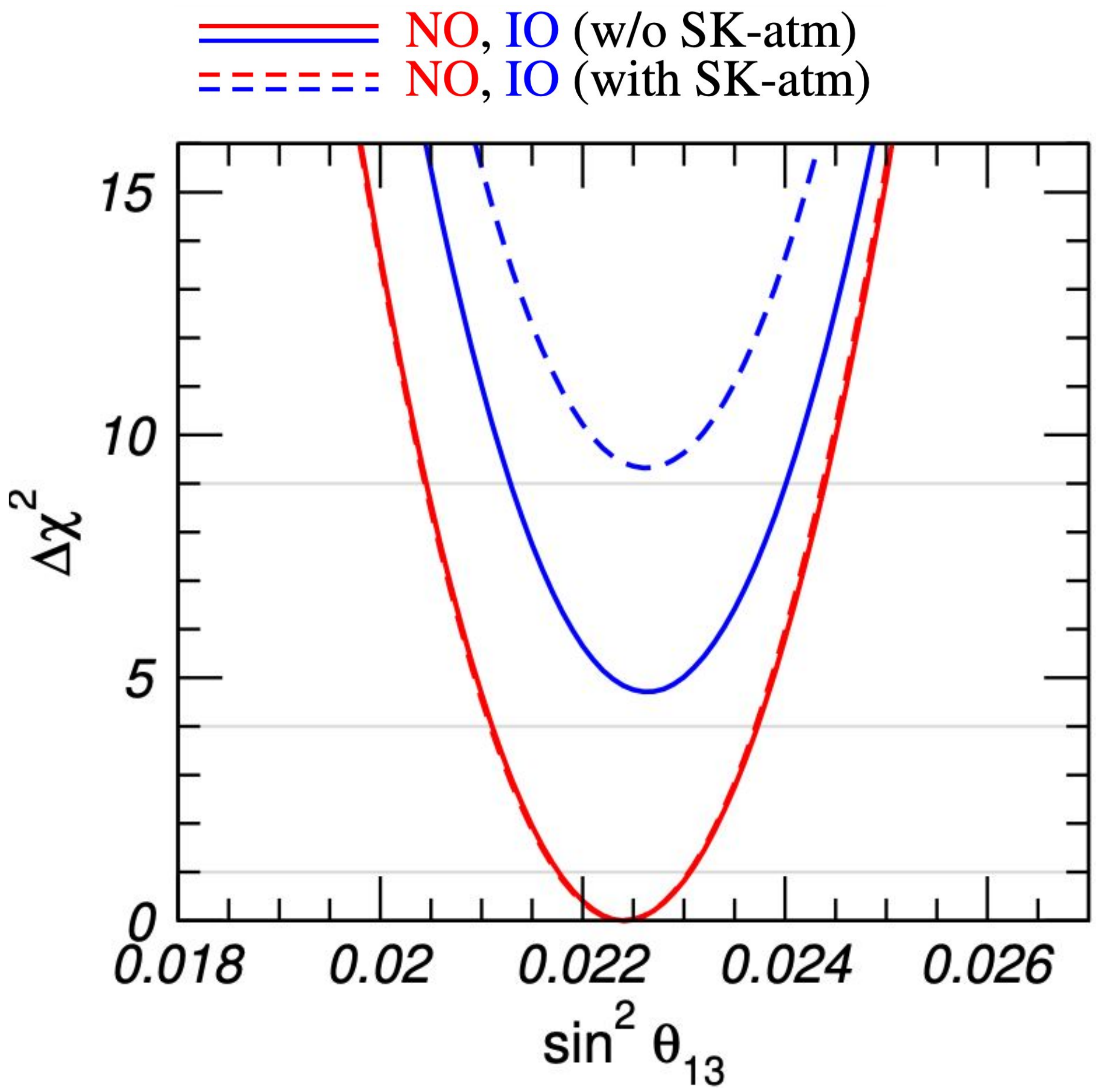
- Also **trivial** to produce a posterior distribution in some **new variable** that is a function of the variables included in the MCMC
  - I.e. if you have a posterior for **α** and **β** → easy to produce any distribution of **$f(\alpha, \beta)$**

Reactor Constraint

- So far results shown have use a flat prior in $\sin^2(\theta_{13})$
  - Check **DUNE's** sensitivity

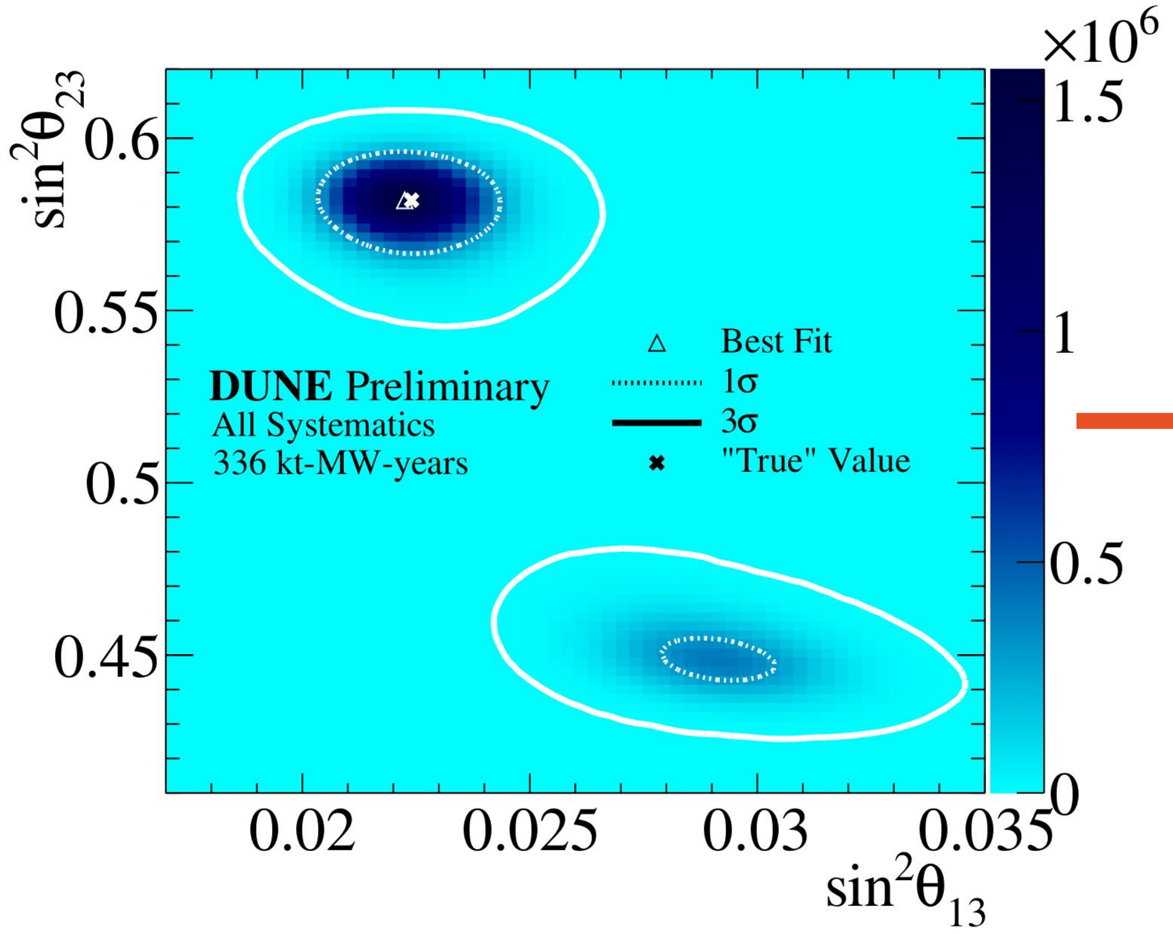
- Currently well-measured by multiple reactor neutrino experiments → dominated by Daya Bay (arXiv:1203.1669)

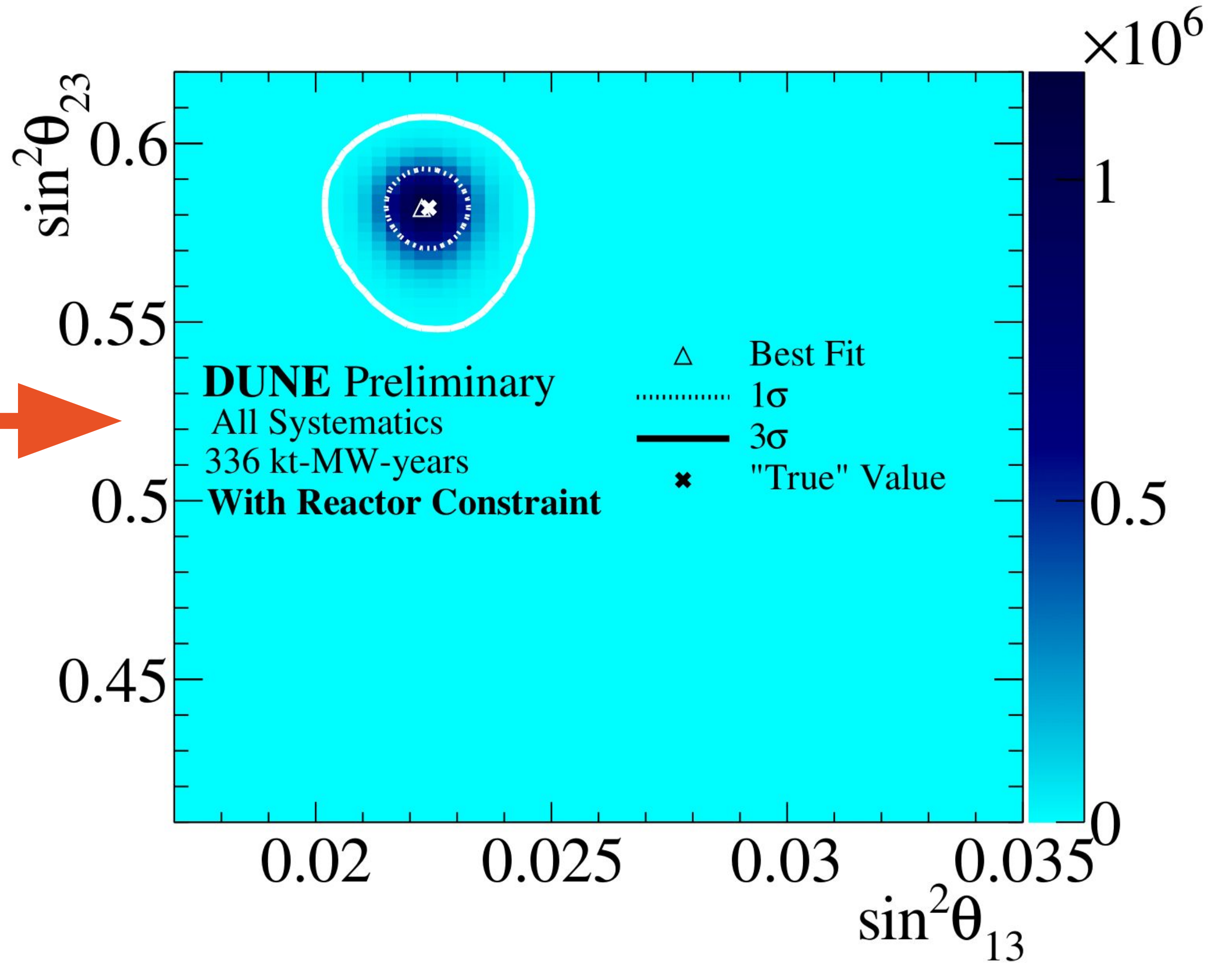
- Reweight posterior with a Gaussian prior → central value and uncertainty from NuFit 4.0



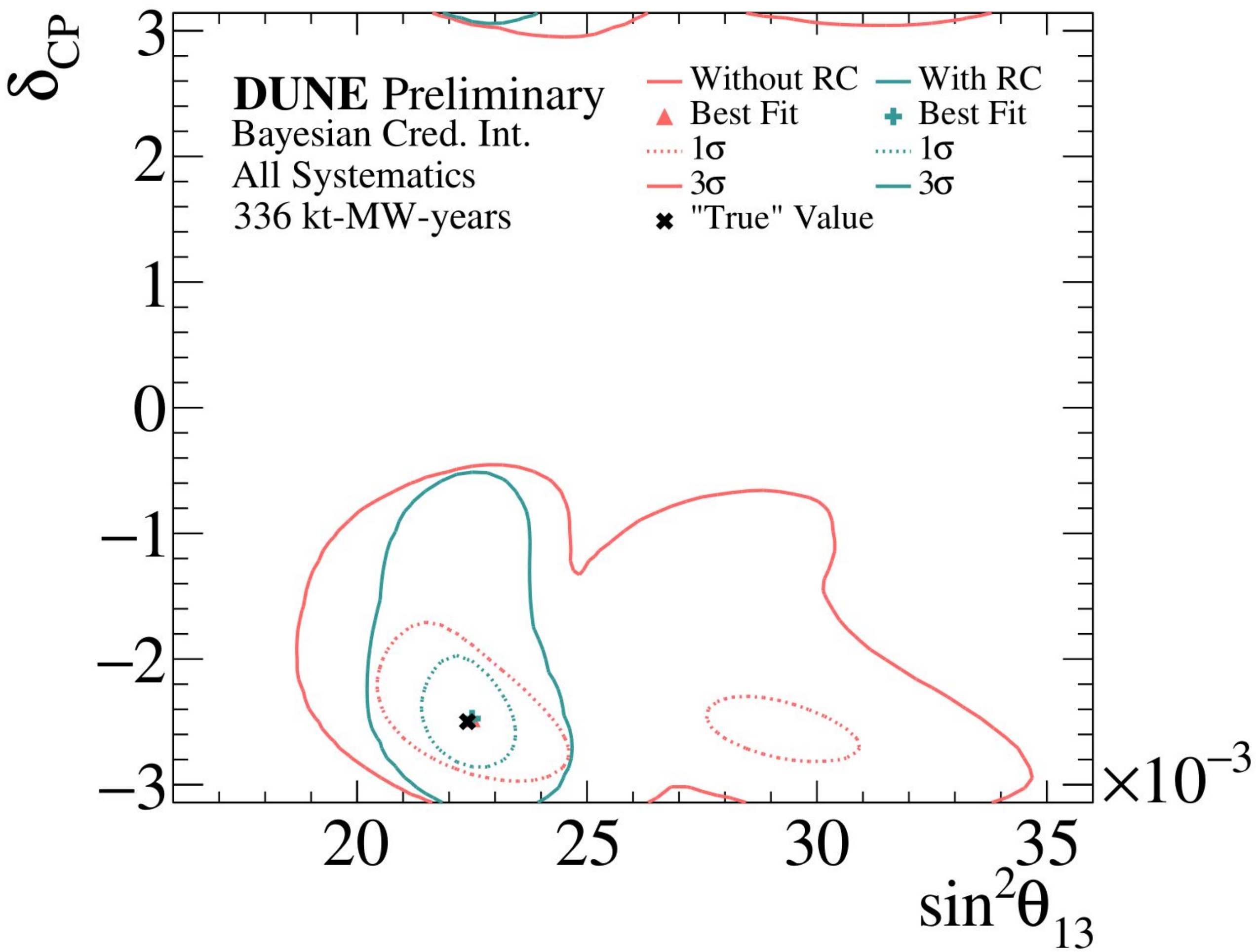
NuFit 4.0 (2018)

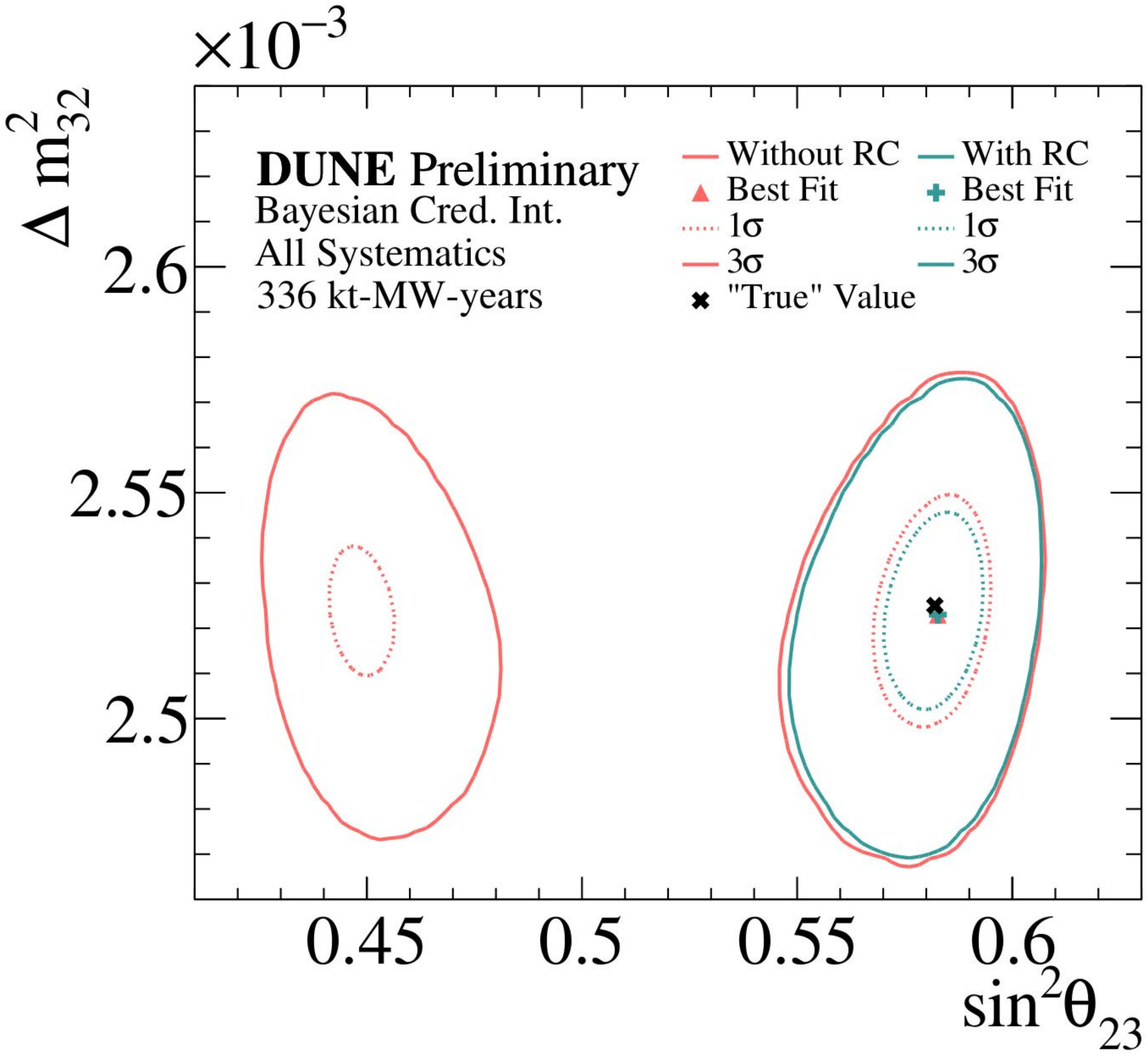
Reactor Constraint





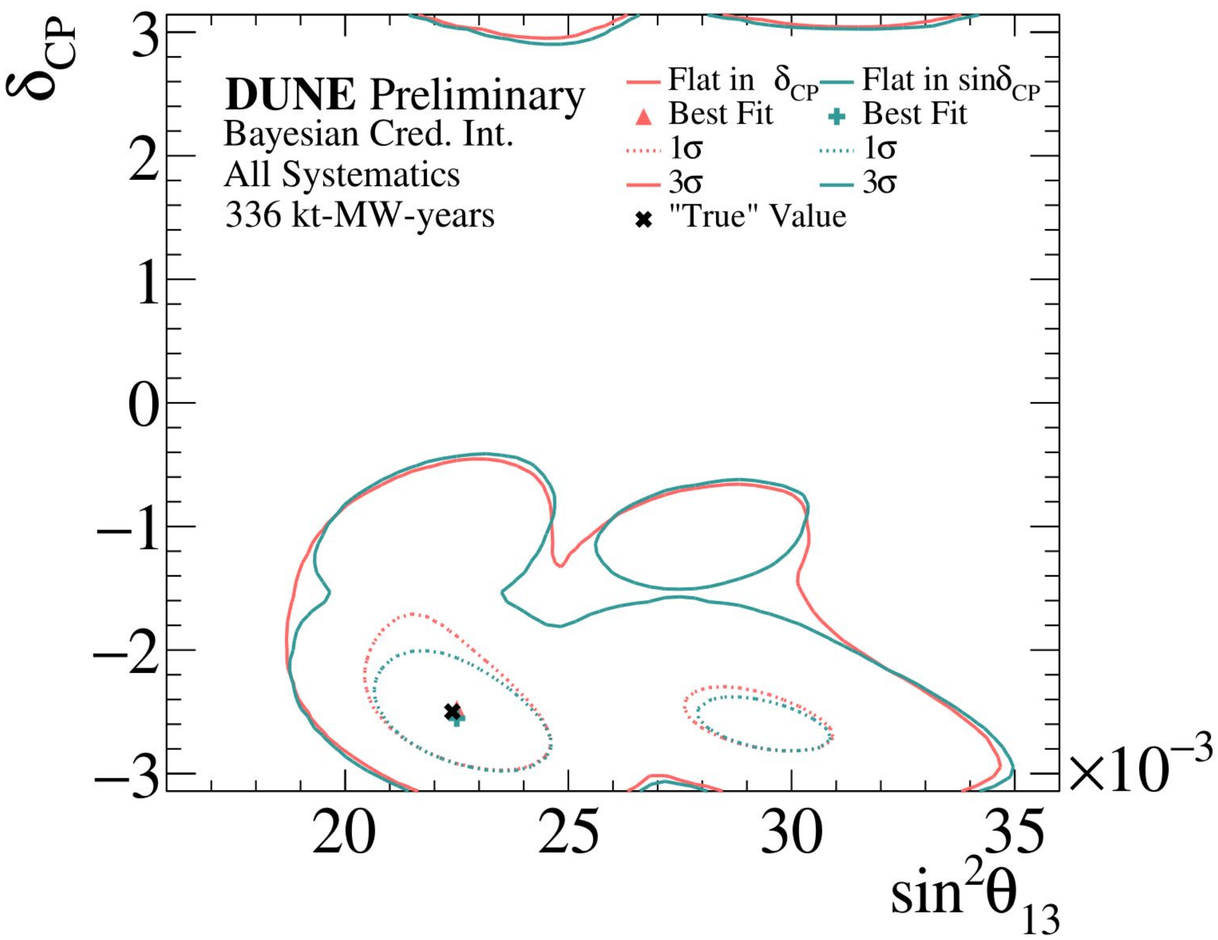
Reactor Constraint

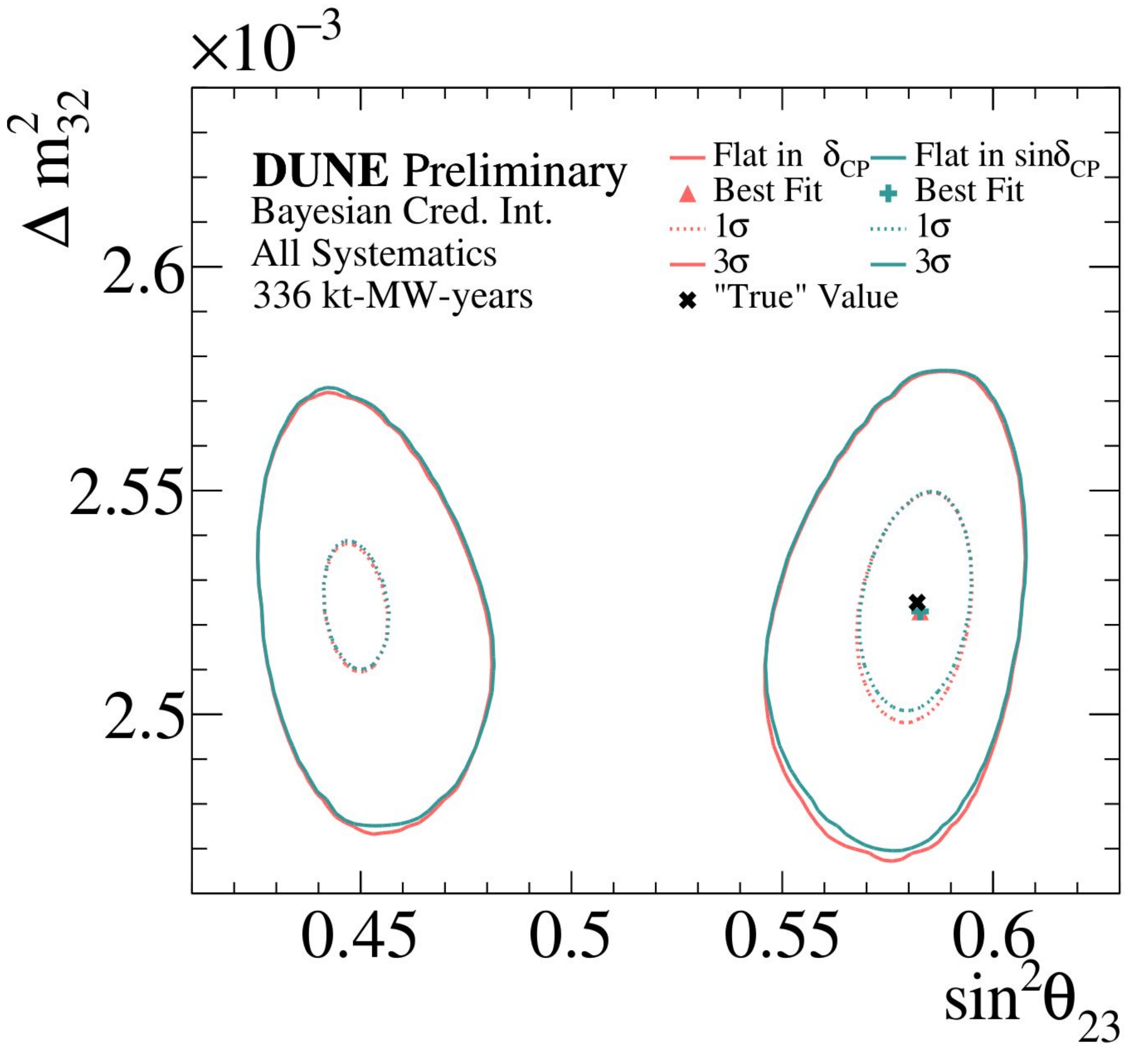




- Second θ_{13} peak completely suppressed
- Wrong θ_{23} octant also suppressed

δ_{CP} Prior Change



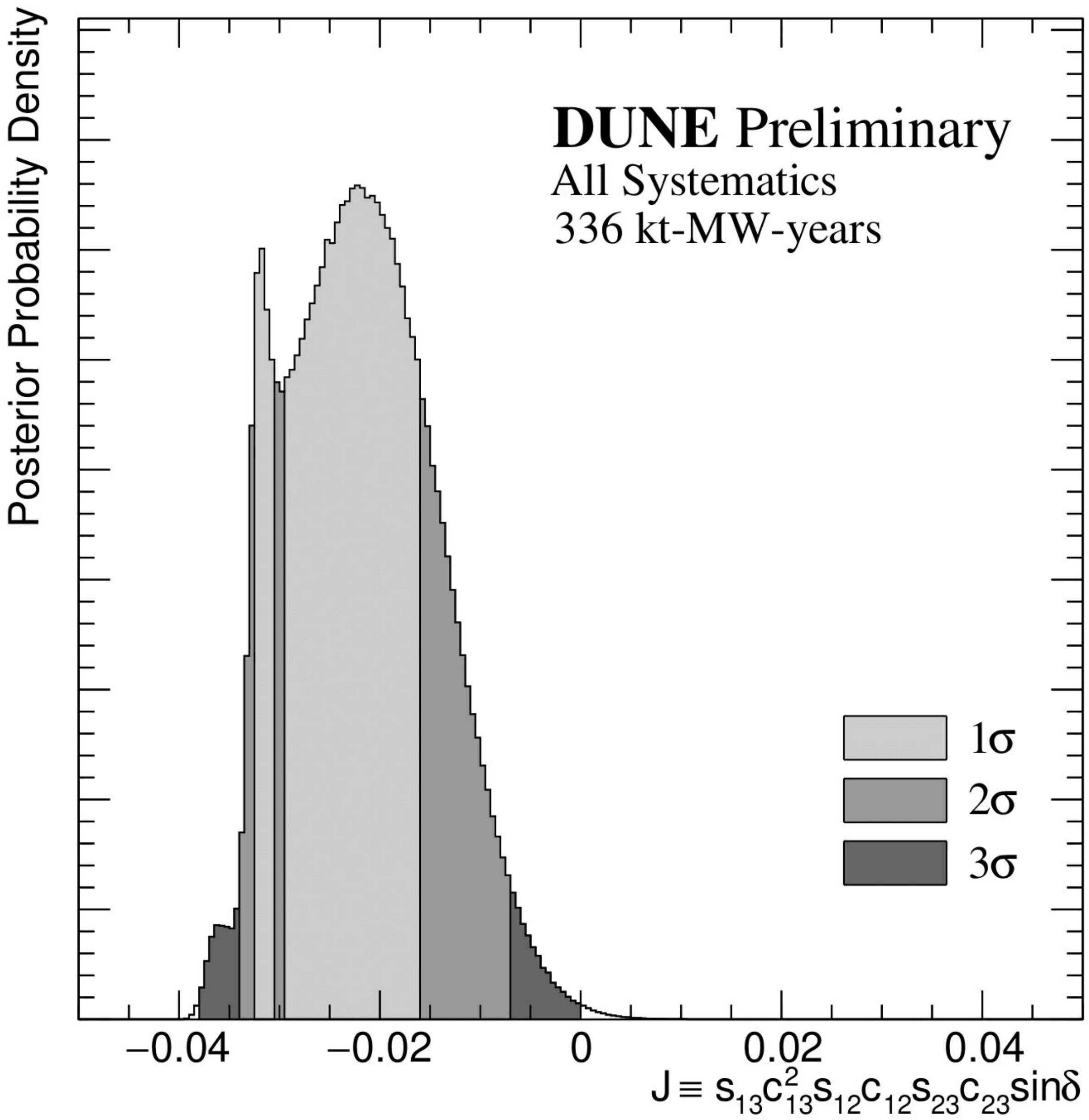


- Flat prior in **δ_{CP}** results in **non-uniform prior** in other quantities e.g. **$\sin\delta_{CP}$** or **$\cos\delta_{CP}$**
- Flat **$\sin\delta_{CP}$** prior of interest → **CPV is a function of $\sin\delta_{CP}$**

Jarlskog Invariant

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

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



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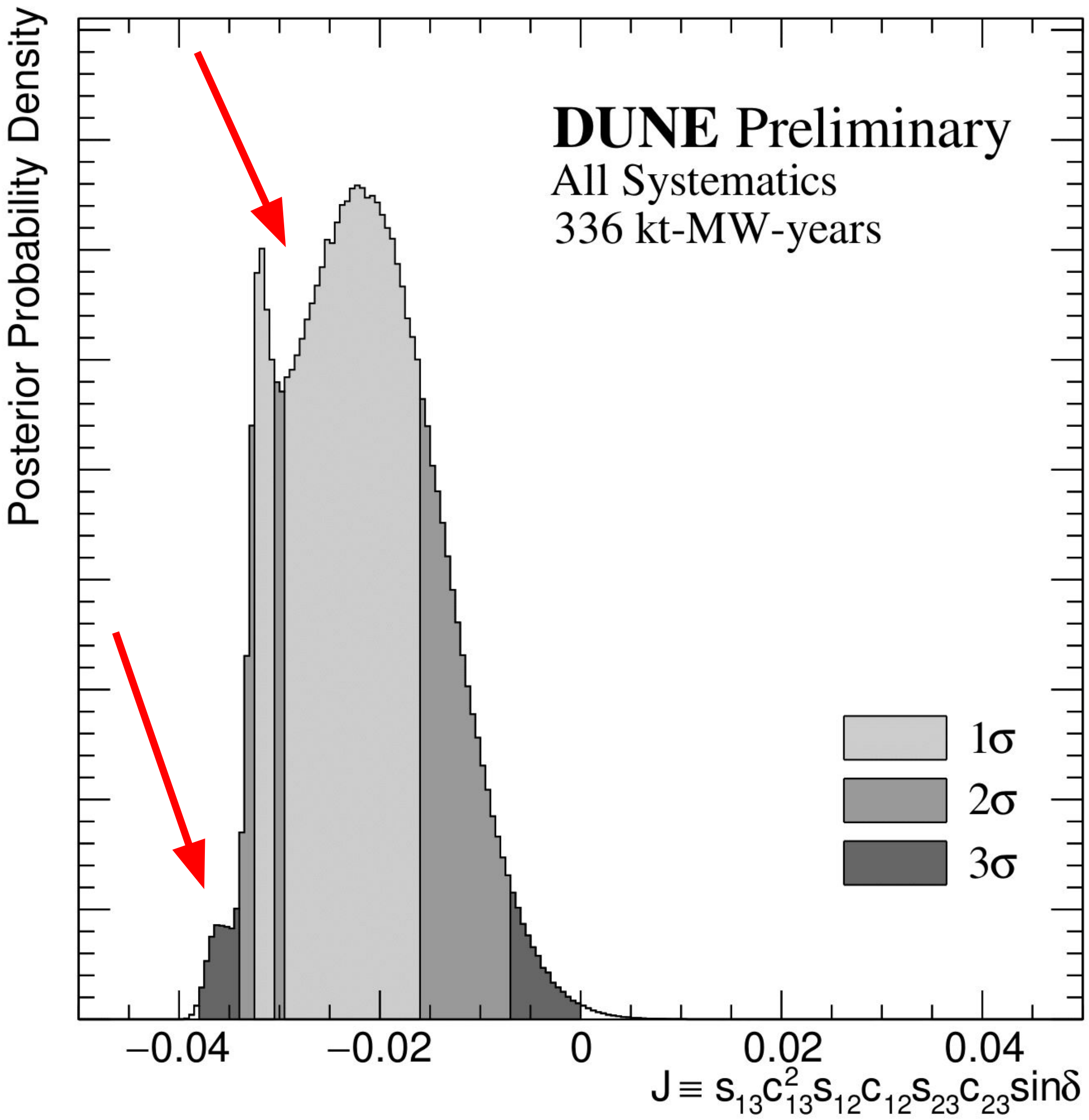

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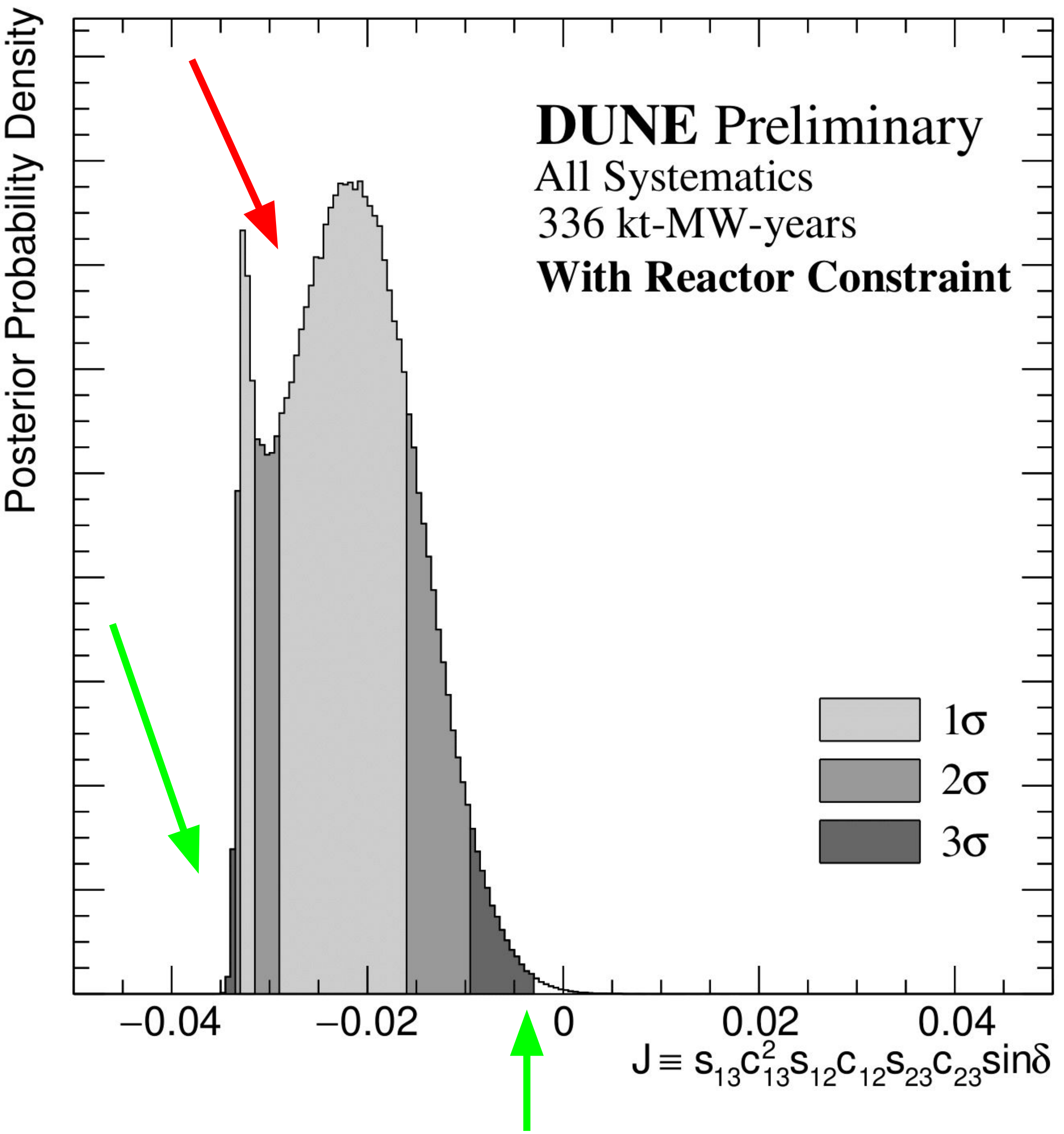
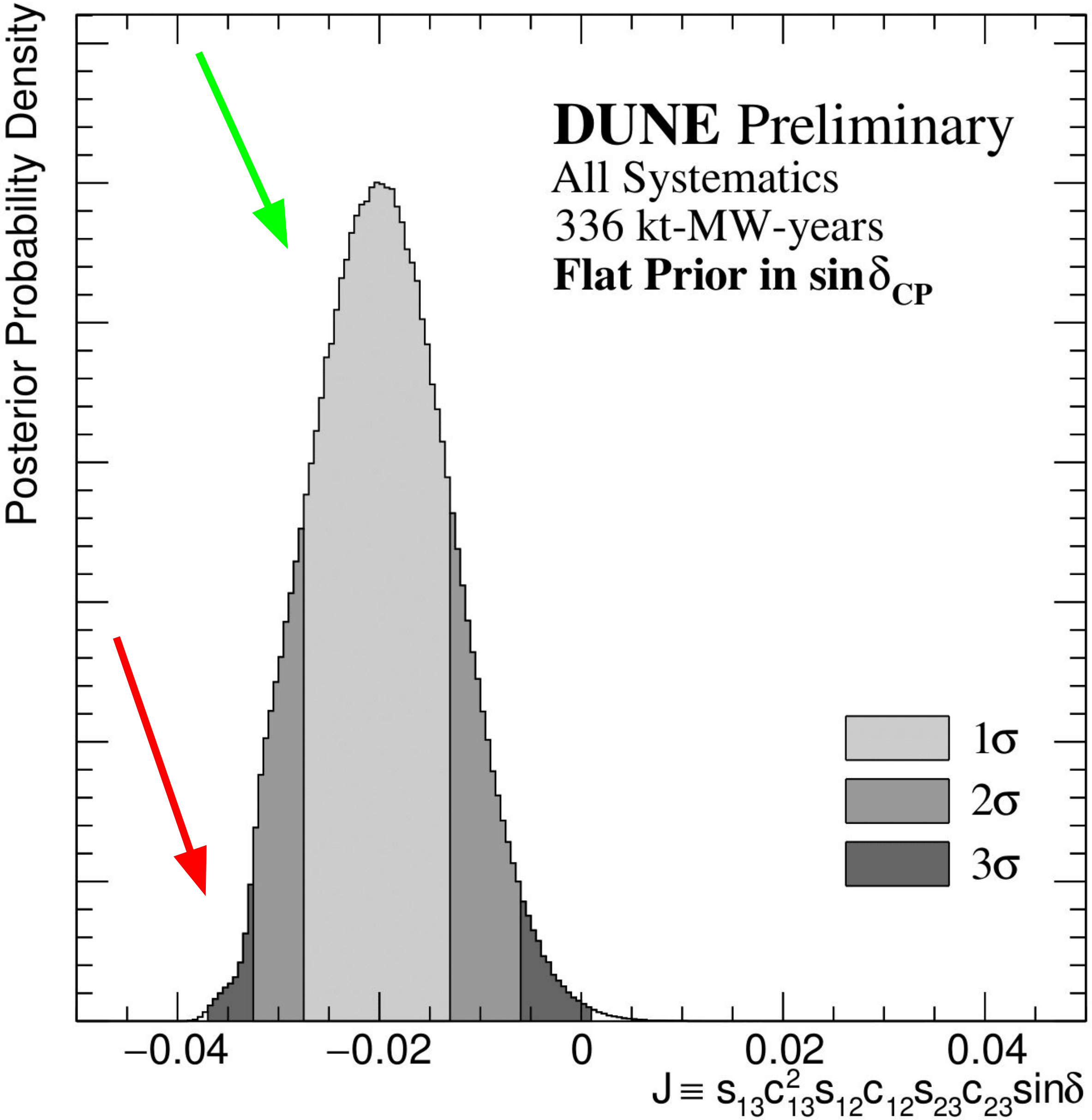


Science and Technology Facilities Council

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 sinδ_{CP} prior:**
  - Removes **dip around peak**

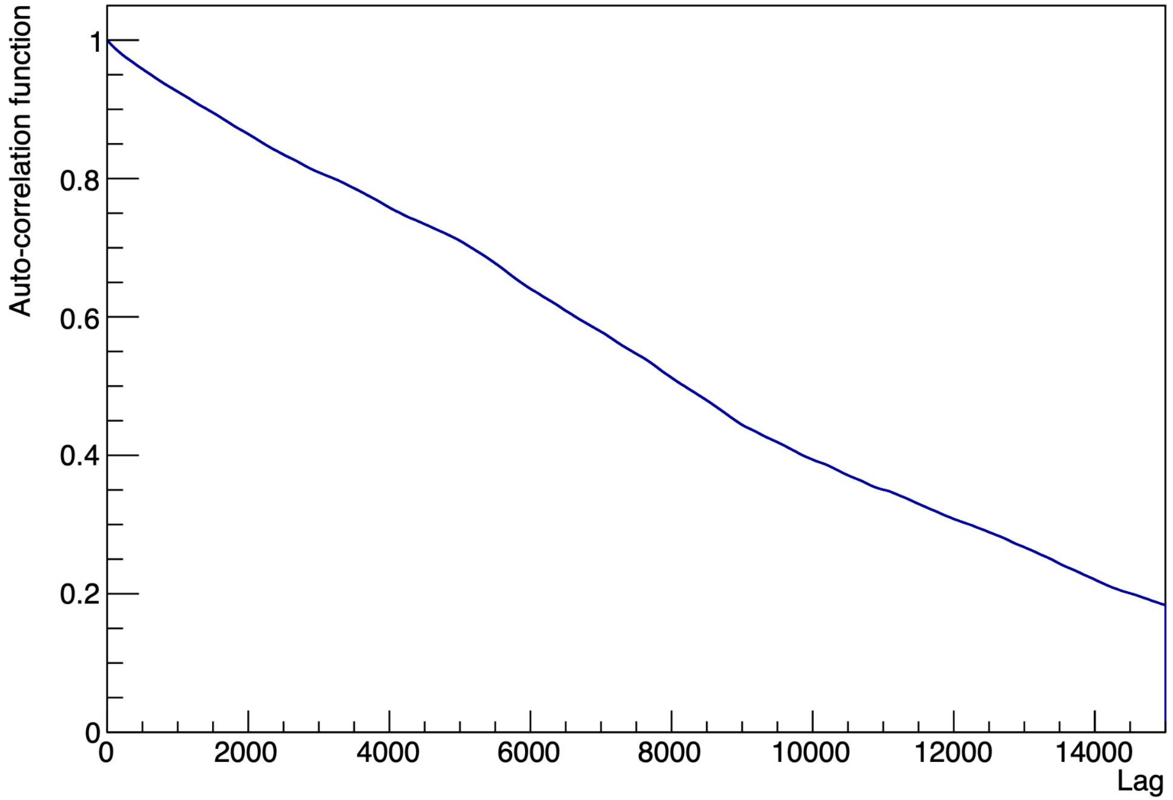
$$J_{CP} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})\sin\delta_{CP}$$



Improved MCMC Sampling

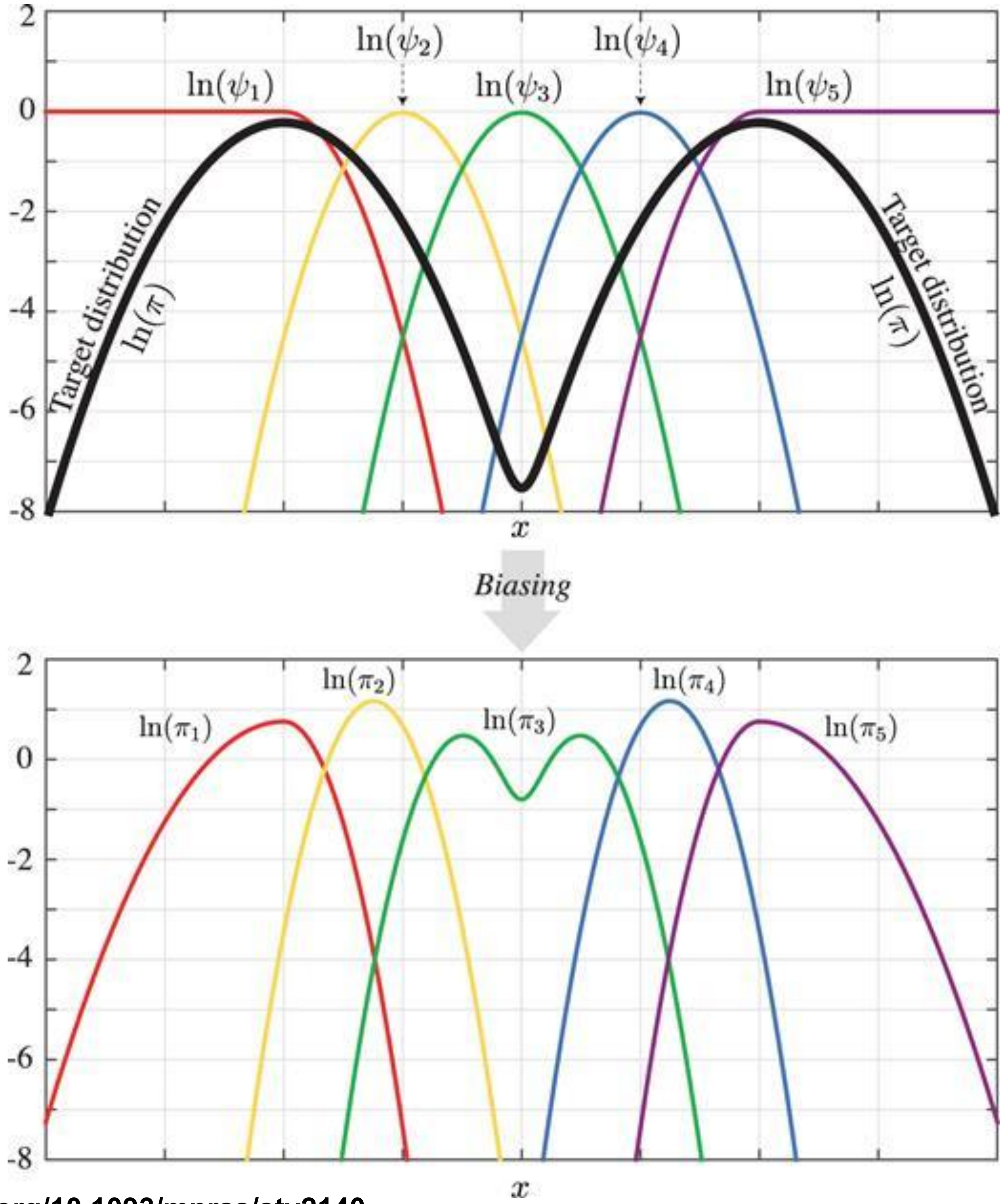
3σ → 5σ Feasibility

- Steps are correlated → ~ **10k** steps to get an **independent step**
  - 180 million steps —> ~ **40** independent points outside the **3σ contour**
  - **Enough to confidently determine where the 3σ contour lies**
- For the same number of independent points outside the **5σ contour** requires **5000x more steps**
  - **~ 800 billion steps!**
  - Would currently require **> 1 billion CPU hours**
- This is **unfeasible!**
  - We need a more efficient method of sampling the **tail regions**



Umbrella Sampling

- Method of sampling **low probability regions** in a distribution:
  - Sample multiple **biased** likelihoods → bias **increases probability in tail regions**
- Combination of each biased sample requires **weights**
  - Undo the bias from each sample
  - Account for over/under sampled regions as a result of "overlaps"
- Several bias options → **Tempered likelihood** has been tested as a first attempt



https://doi.org/10.1093/mnras/sty2140

Tempered Likelihood

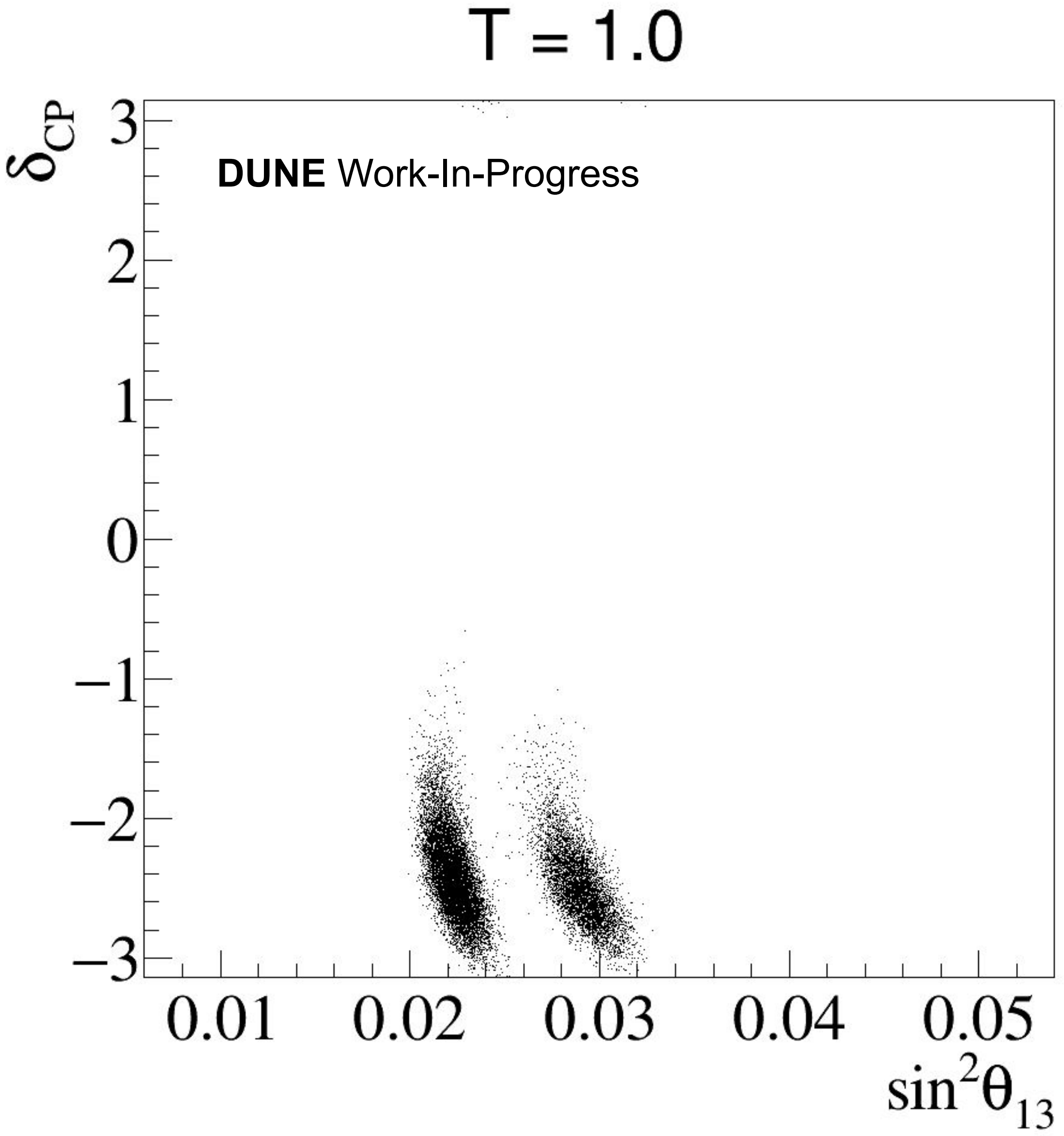
- Flatten entire distribution rather than confining the chain to a specific low probability region
  - Low probability regions explored more frequently

$$\mathcal{L} \rightarrow \mathcal{L}^{1/T}$$

- Higher "temperature" → more flat likelihood distribution
  - Sample at several temperatures → combine together using Umbrella Sampling weighting

Tempered Likelihood

- Effect of temperature on δ_{CP} - $\sin^2\theta_{13}$ distribution:
  - Same number of steps at each temperature
- **Next step**: Combine these chains using umbrella weights
  - Hopefully credible intervals lie where we'd expect them too!



Summary

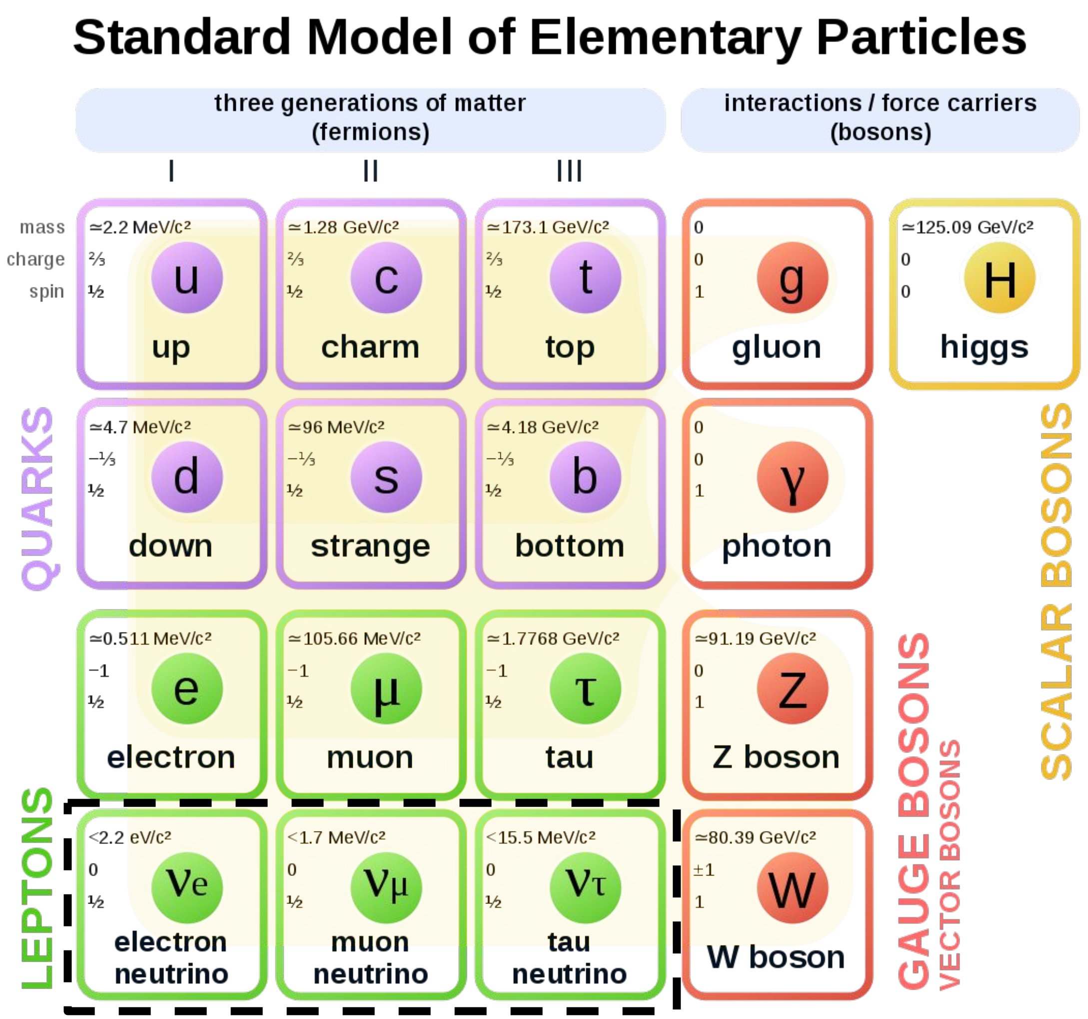
- DUNE will enable **an exciting physics program** and aims to make **precise measurements** of the oscillation parameters:
  - Definitively measure the **MO** regardless of other oscillation parameters
  - Sensitivity to **CPV** and **θ_{23} octant**

- **First Bayesian analysis of DUNE** has been performed
  - **Complementary** to existing and future frequentist sensitivities
  - Provides ability to **update results** based on **new information**
    - Does not require a new fit
  - First in-depth look at alternative quantities e.g. **J_{CP}**

- Exploring **new sampling methods** to reduce computational cost for achieving **high significance measurements**

Back up

Neutrinos



- **Three** generations of matter:
  - Three charged **leptons**
  - Three corresponding **neutrino flavours**
- Neutrinos…
  - **Neutral**
  - Massless (**in SM**)
  - Interact via **weak force**

DUNE Physics Goals

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

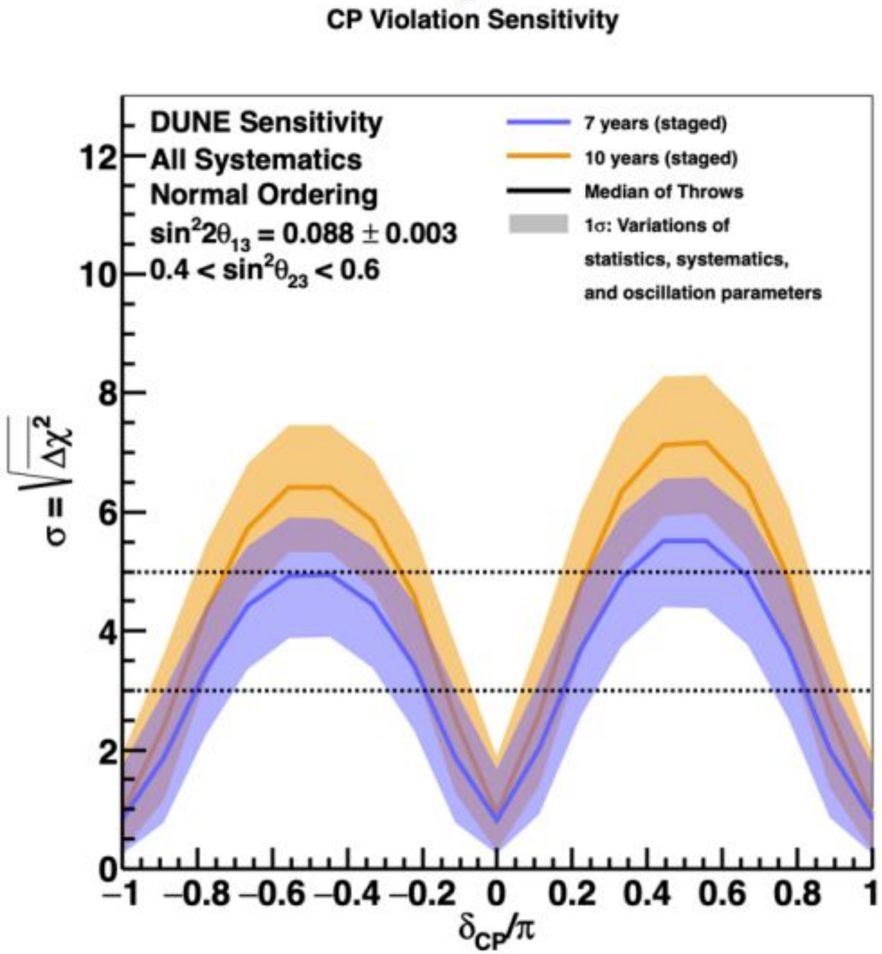
1. Make precise measurements of the oscillation parameters θ_{23}, θ_{13} and Δm_{32}^2
2. Resolve the neutrino mass hierarchy, i.e. whether $m_3^2 > m_2^2$ or $m_3^2 < m_2^2$
3. Determine the octant of θ_{23}
4. Determine whether CP is violated in neutrinos and make a measurement of δ_{CP}
5. Search 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 .

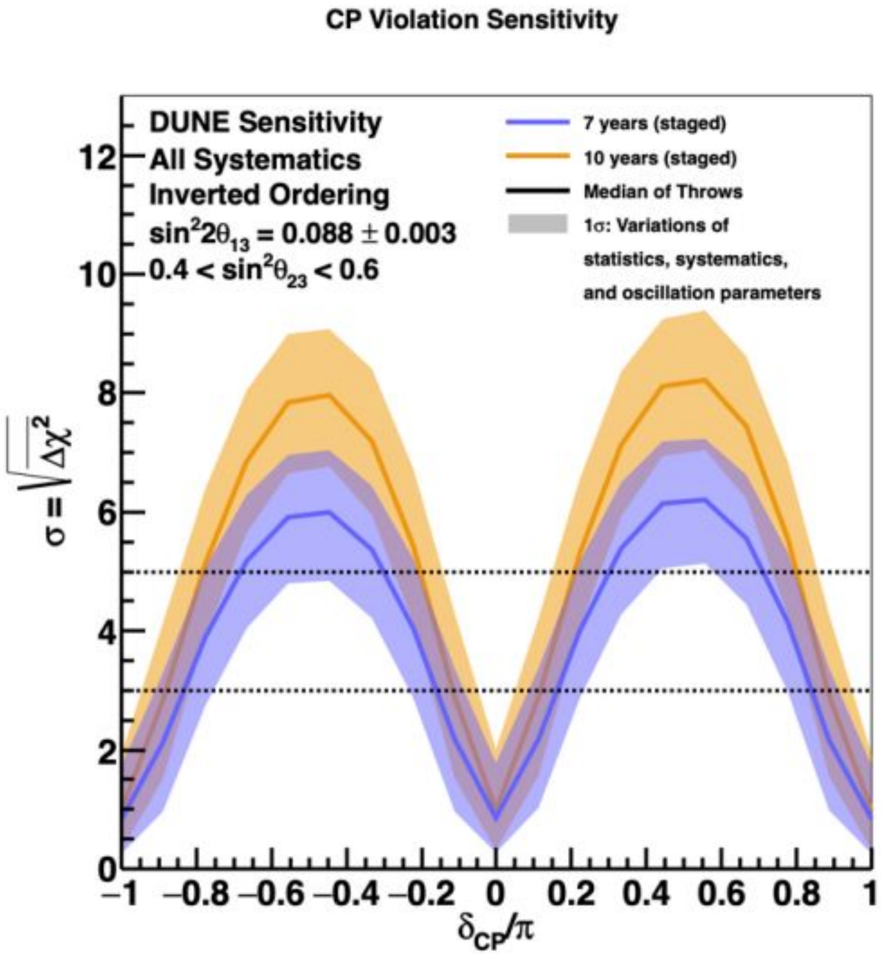
NuFit 4.0 Parameters

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

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

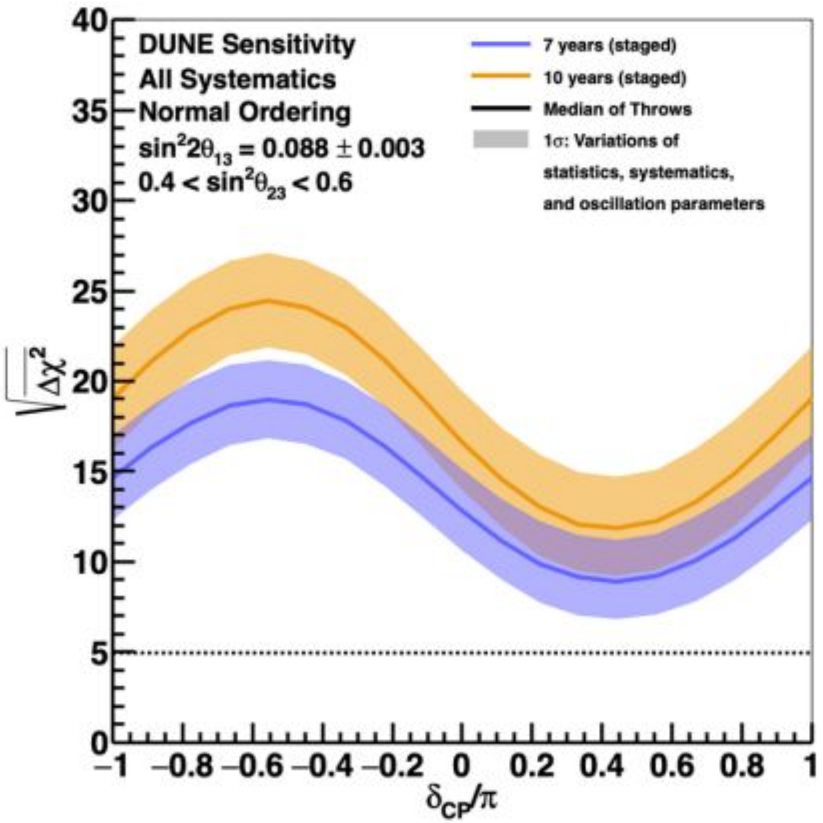
CPV Sensitivity

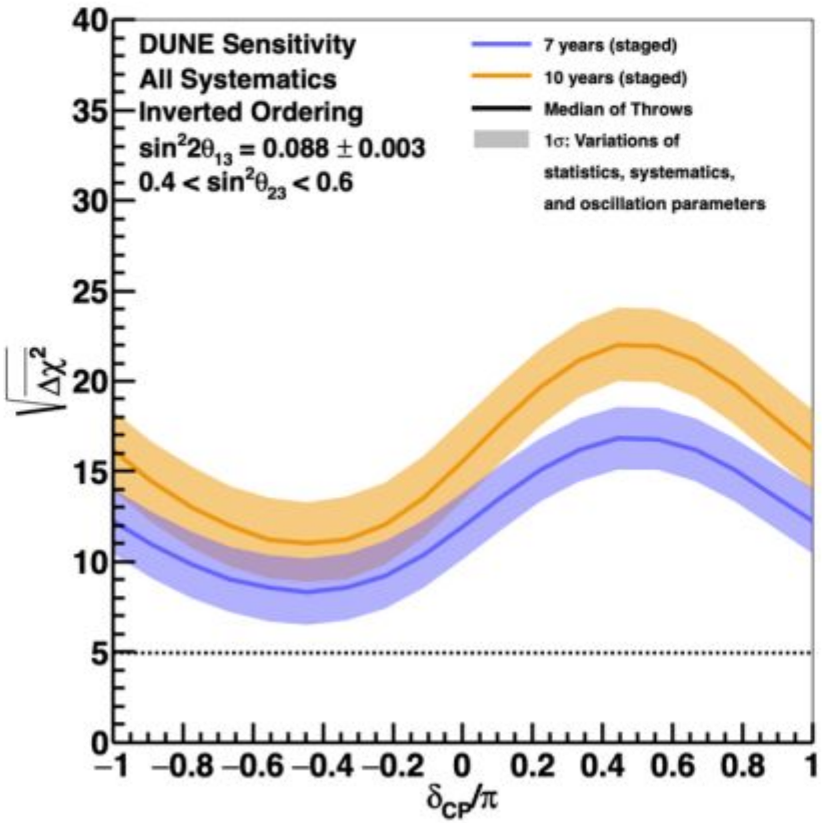




- After 10 years (staged), there is significant CP violation (**$\delta_{CP} \neq 0, \pi$**) discovery potential across true values of **δ_{CP}** and for both hierarchies

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