DUNE Oscillation Sensitivities using MaCh3

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How Do Long-baseline Analyses Work?

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

- We have a **large number of events (ND + FD)** at DUNE - need to **constrain our systematics**
- How do we do that? **Near Detector! O(100 million), no oscillations!**
- Far detector has **far fewer** events and **oscillations** -> apply systematic constraints

Why is this difficult?

- Systematic model needs to be **complex** - **extrapolating between very precise ND complex ➤ huge FD with different systematic uncertainties**
    - **True energy -> reco energy map** key to extracting true parameter values

- Simplified model will cause **bias/over-constraints**

- Uncertainties are degenerate with each other

- ND data will pin down each systematic -> encountered by **Technical Design Report (TDR) analysis**

Toy Example:

- **Systematic X** applies to **ND and FD events**

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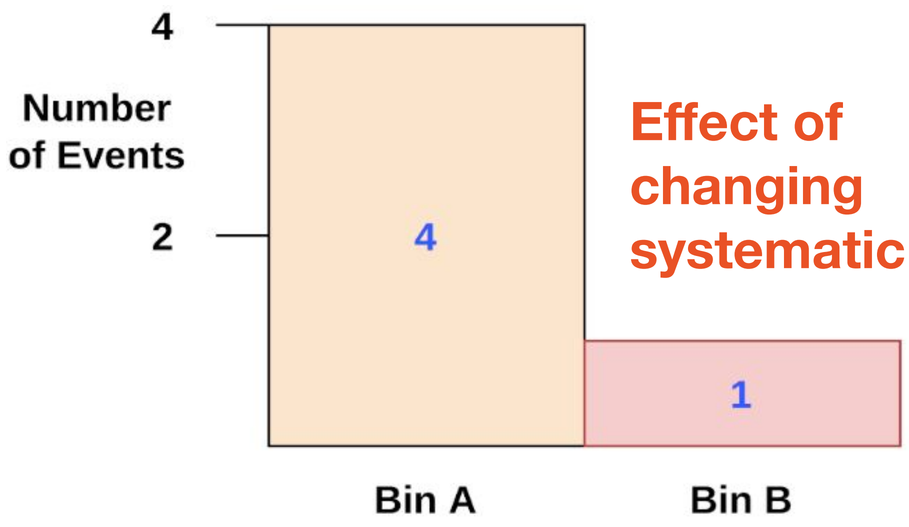
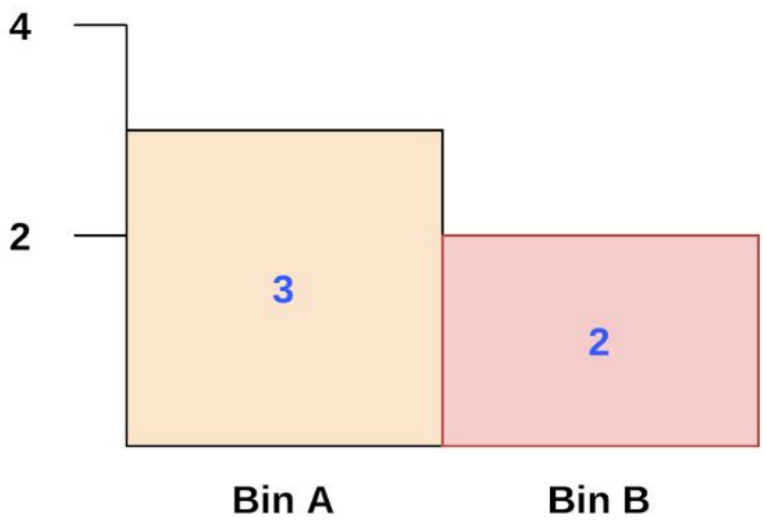


Effect of changing systematic X



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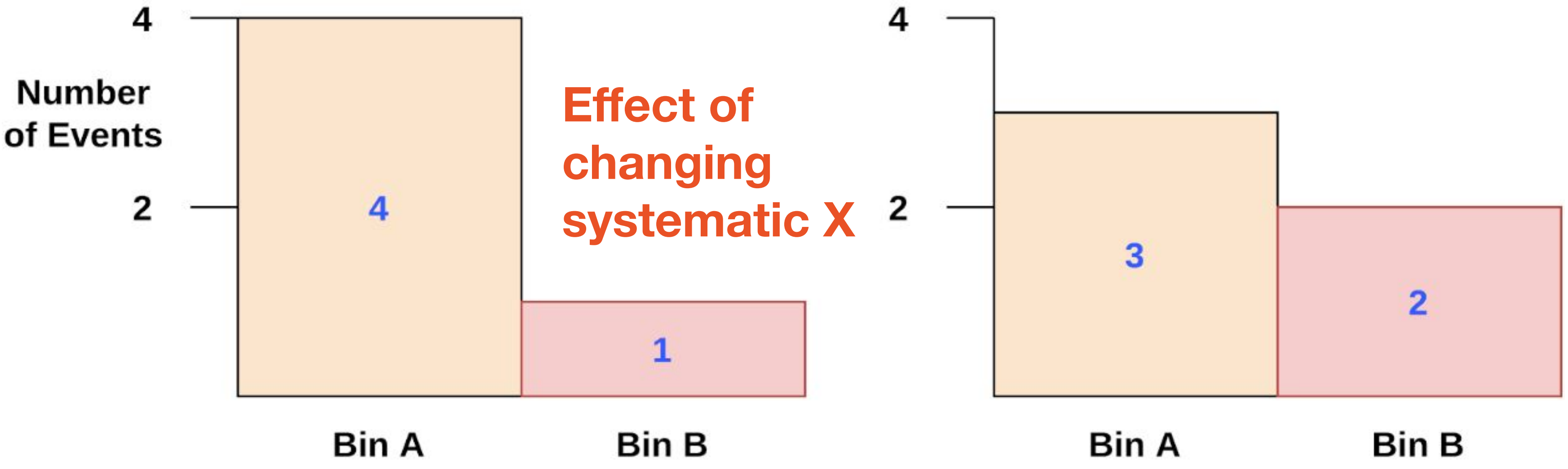

ND will work out exact value of systematic X!

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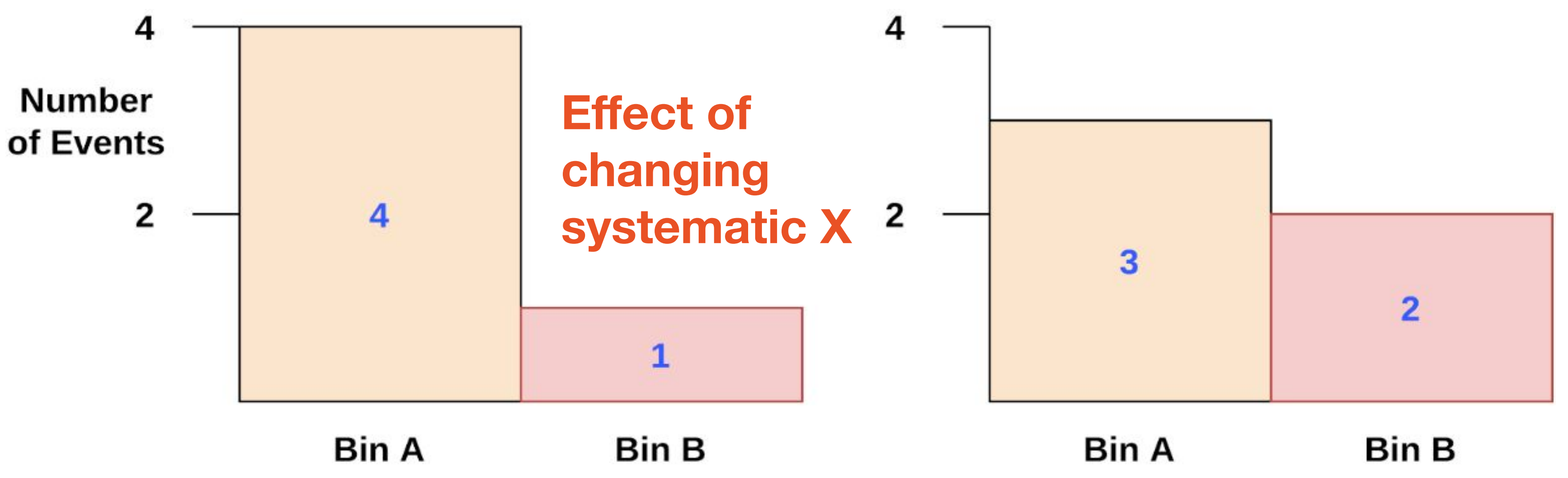

ND will work out exact value of systematic X!

- Add **systematic Y** which **only affects ND** also **shifts events from A->B** = **degeneracy**
- Now ND **can't work out value of systematic X**

MaCh3 - A Markov Chain Monte Carlo Fitter with a built-in Likelihood Calculator

Evaluate the likelihood

- **Binned Likelihood Analysis**
- We need to model this complex/degenerate likelihood space -> **different types of systematics:**

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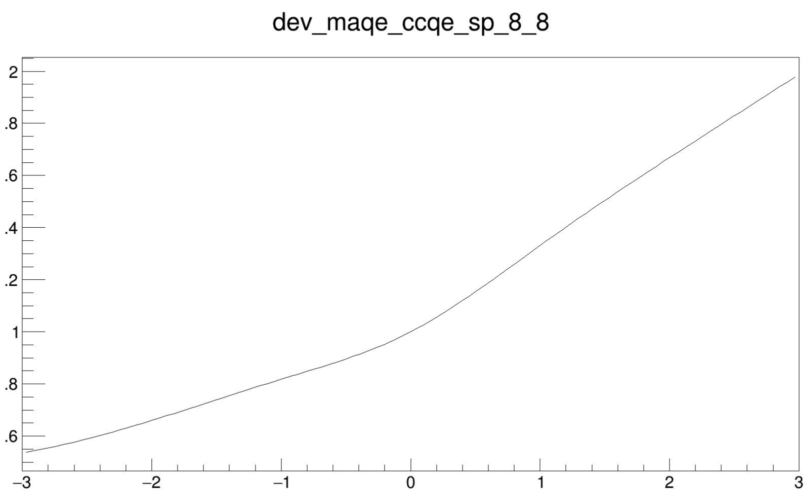

- Continuous response functions using piecewise cubic interpolation
- Binned or **event-by-event**
- Cross-section parameters

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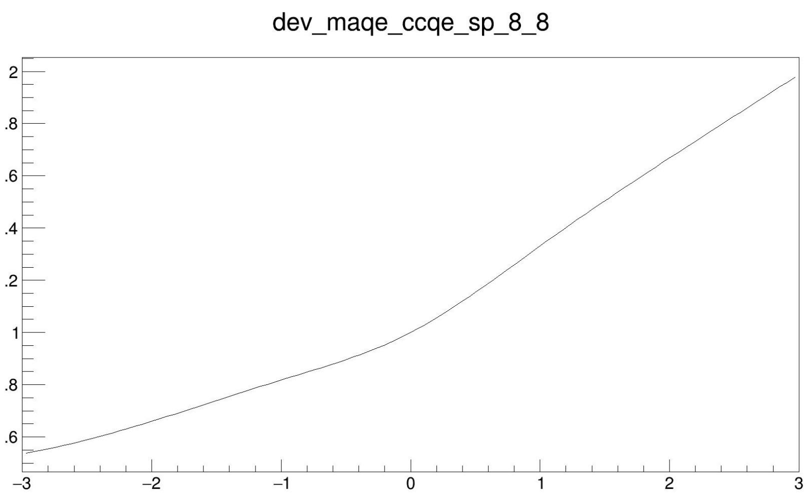

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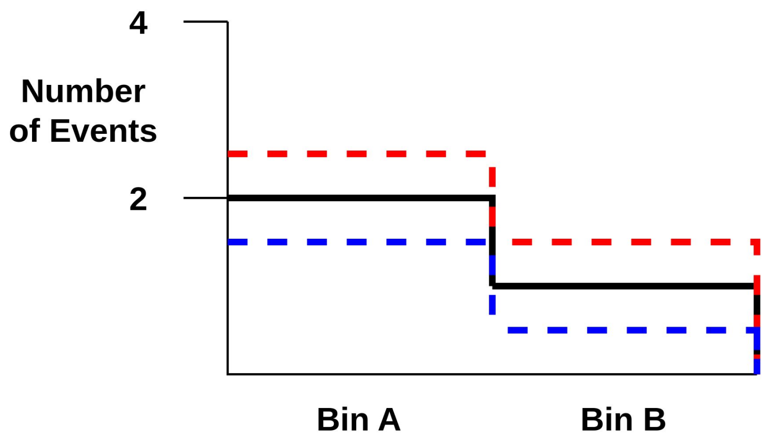

- Weights events up and down relative to parameter movement
- Apply to specific kinematic ranges and events
- Flux parameters

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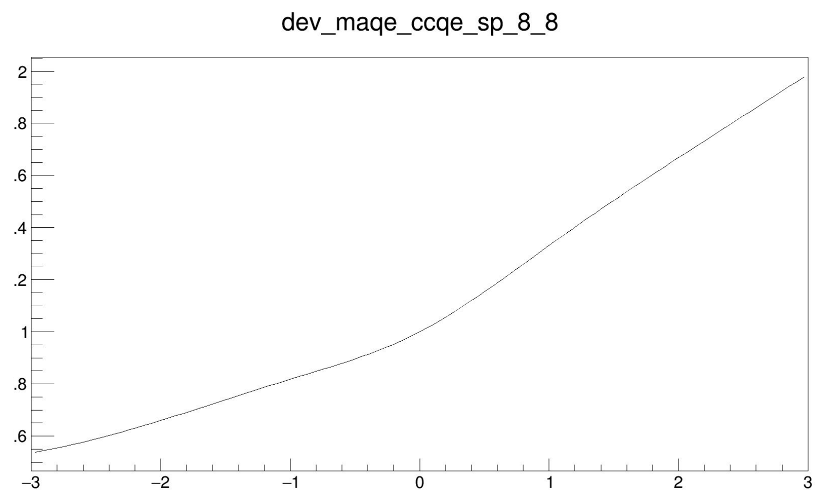

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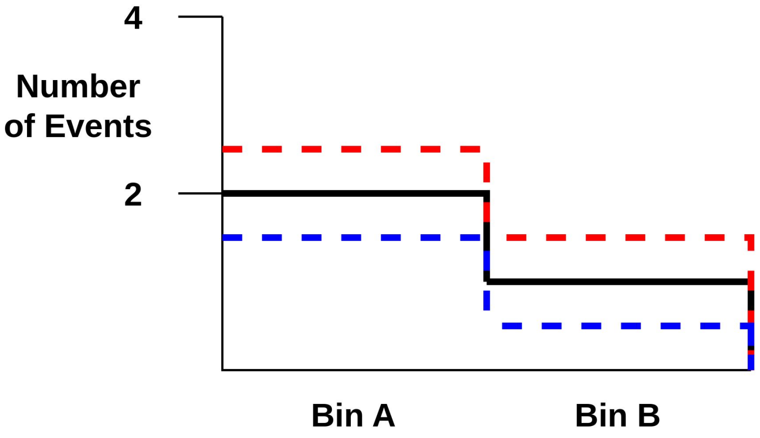

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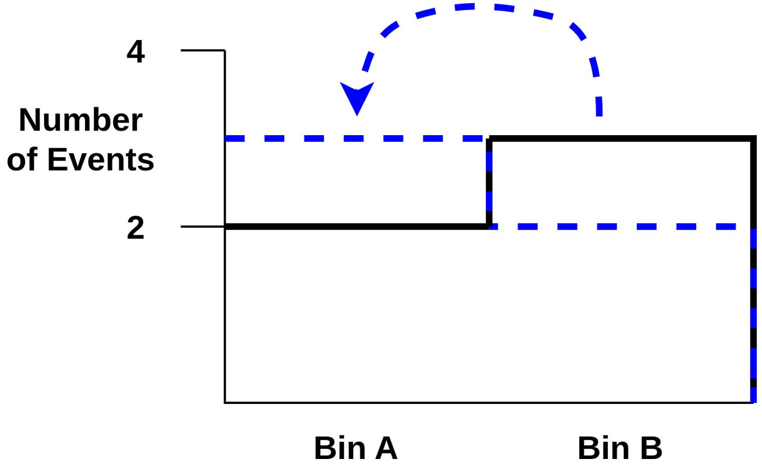
Shift-like



- Move events from one bin to another
- Systematics which **change reconstructed variables**

Evaluate the likelihood

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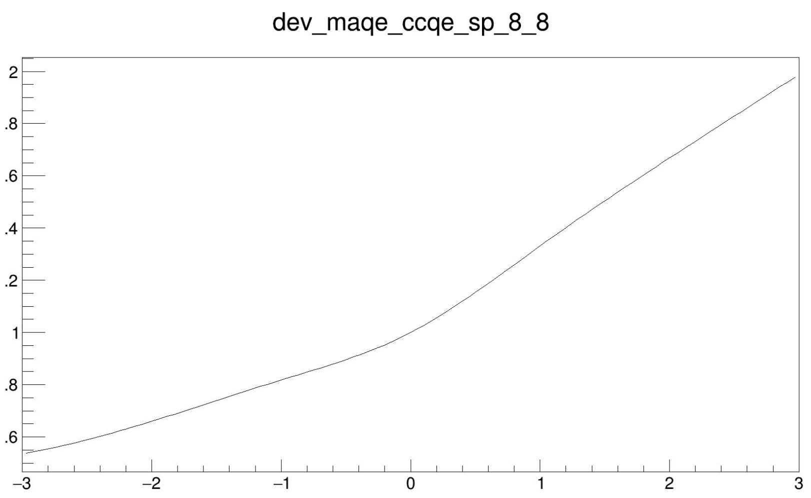

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Normalisation

MaCh3 keeps all event information during a fit

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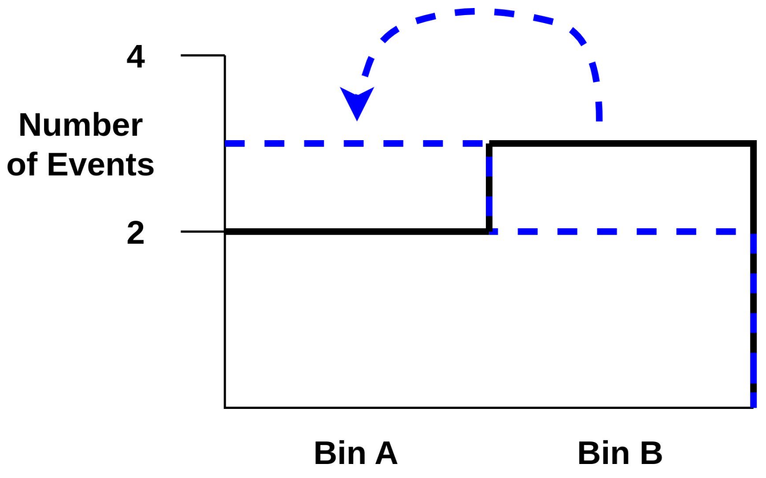

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How do we explore this complicated likelihood space…?

- Likely 500+ parameters total
- Discontinuous
    - Events moving between bins and samples
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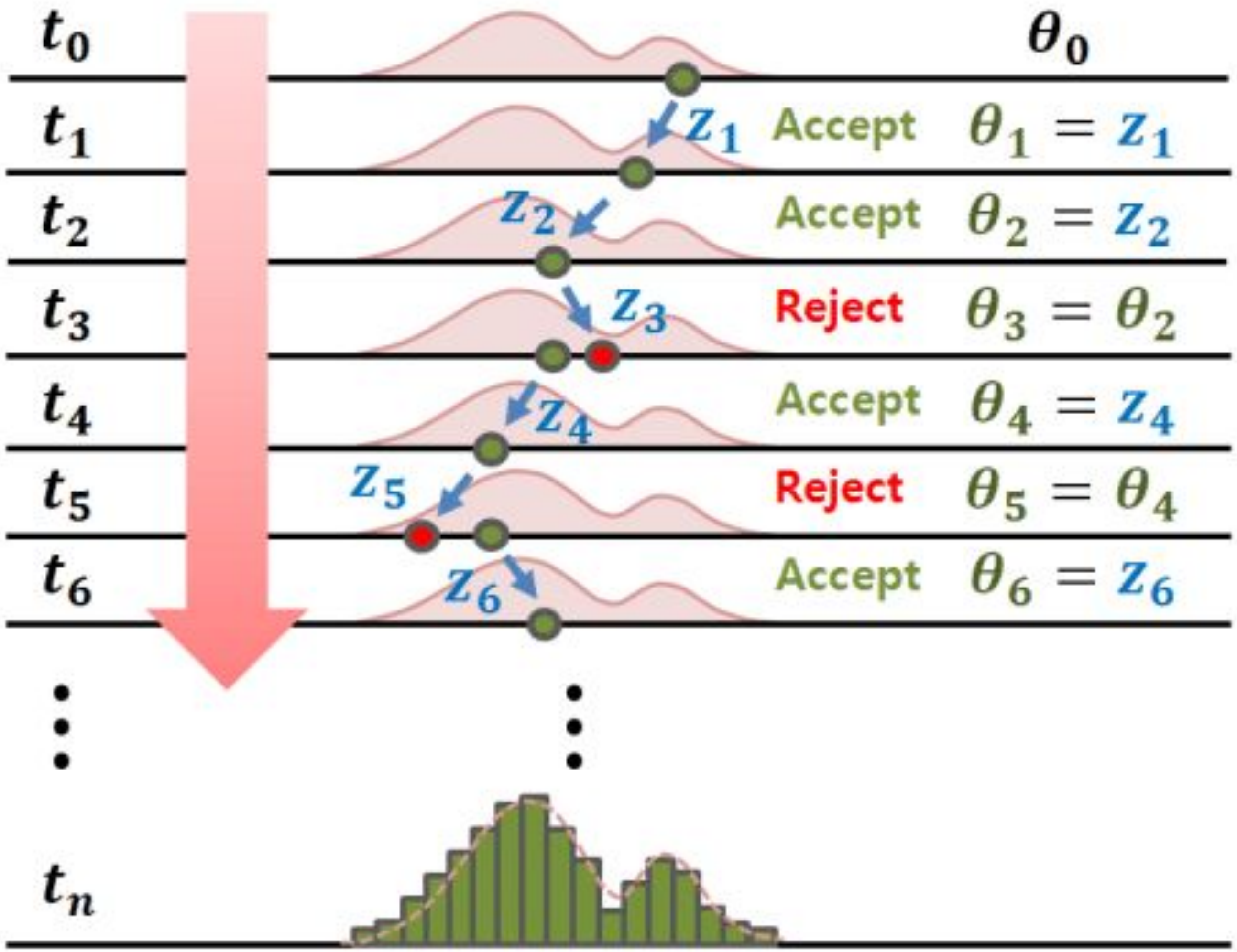
*** MCMC has entered the chat ***

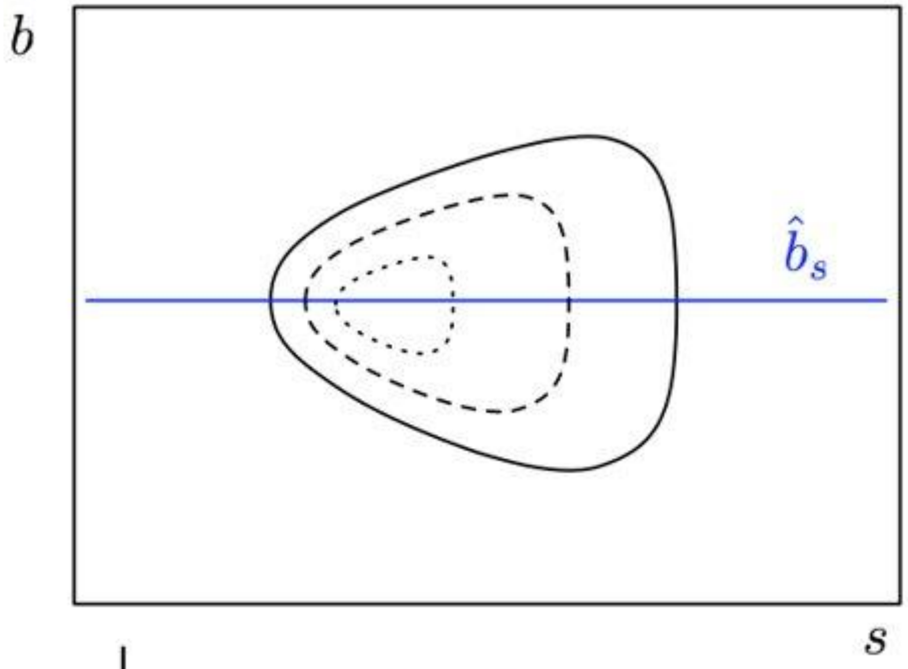
MCMC - Markov Chain Monte Carlo

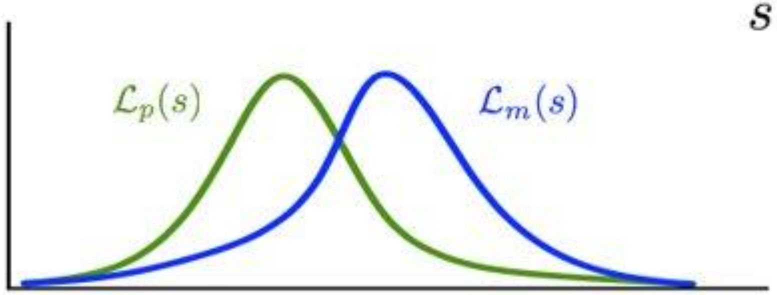
- Semi-random walk around the **full** parameter space
- Metropolis-Hastings algorithm for **accepting** or **rejecting** steps
- Builds up distribution of steps in each parameter -> **proportional to target distribution**
- Scales well with dimensions
- Can deal with **discontinuous likelihoods** (caused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





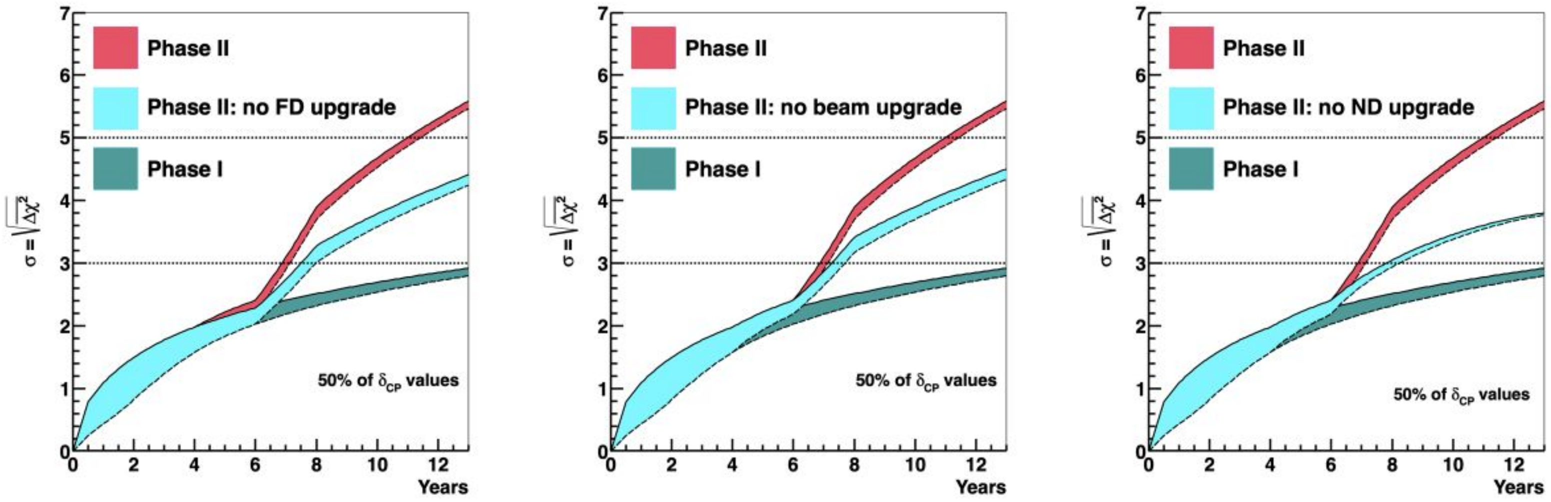
Bayes' theorem:

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

Current motivations for this analysis

- Sensitivity studies - **can DUNE do what it hopes to do**?
- Motivate **design choices** for DUNE
  - How will this complex Near Detector affect our sensitivity?
  - Prove that we do need it!
- Check how systematics behave in these large fits
- Check out our fits behave with much larger statistics

Snowmass Neutrino Frontier: DUNE Physics Summary arXiv:2203.06100

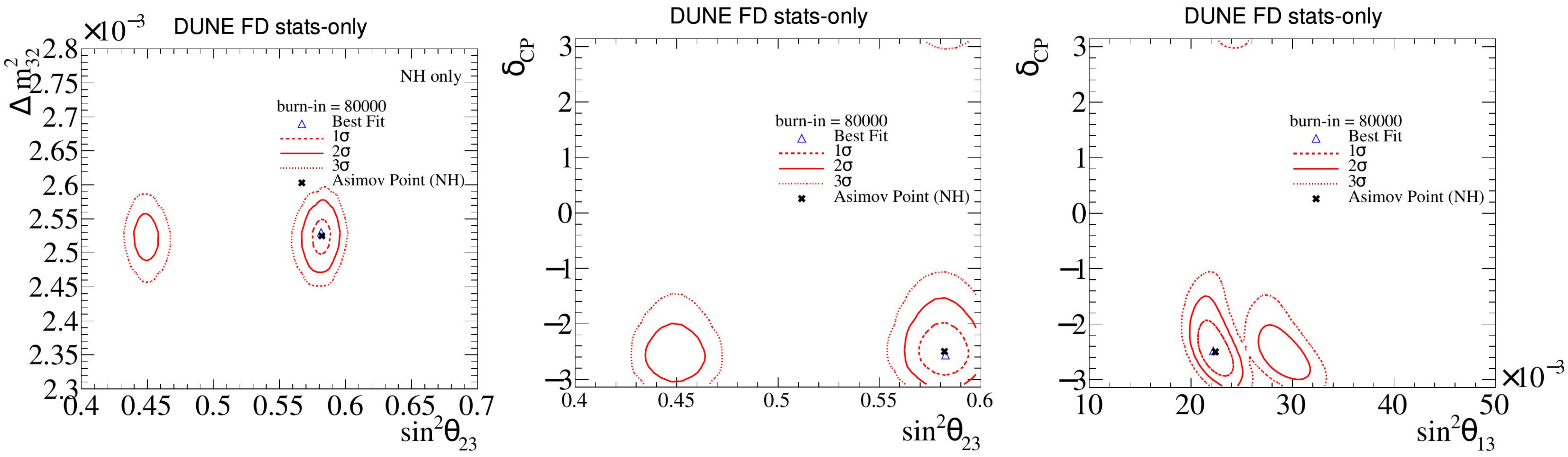


FD-only Sensitivities

FD-only Asimov fits

- Fits were run with **27 million** steps for **stats-only** & **104 million** steps w/ **flux+xsec systs**
- **NuFit 4.0 NH** Asimov point chosen for comparisons with **DUNE TDR**
- Uses simple TDR model (and no detector systs) -> would look **worse** with **full syst model**
- Using **nominal 7 year exposure -> 336 ktMWyr** and **without reactor constraint**
- **Step sizes** for **systematic parameters** have been tuned
- Reweighting binned **in mode and true energy**

FD-only Stat-Only: 2D Contours



- Asimov point and best-fit point lie **in close agreement**
- **1σ contour only in correct octant**

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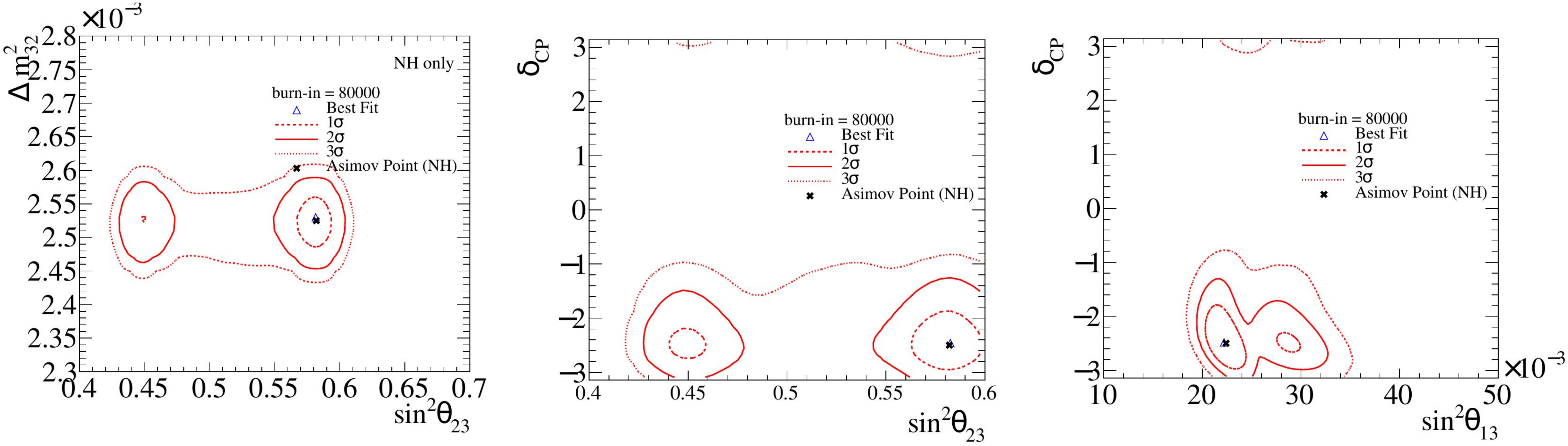
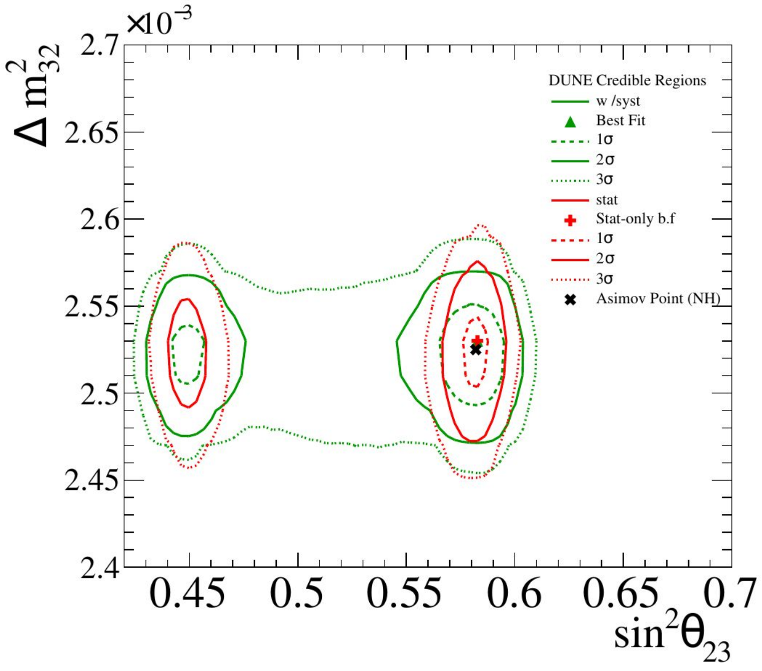
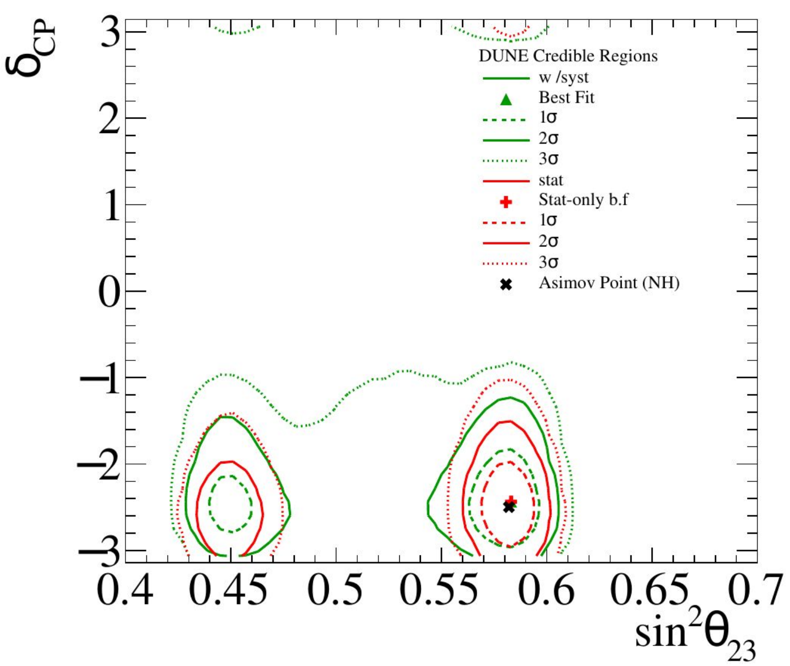
FD-only w/Systs: 2D Contours

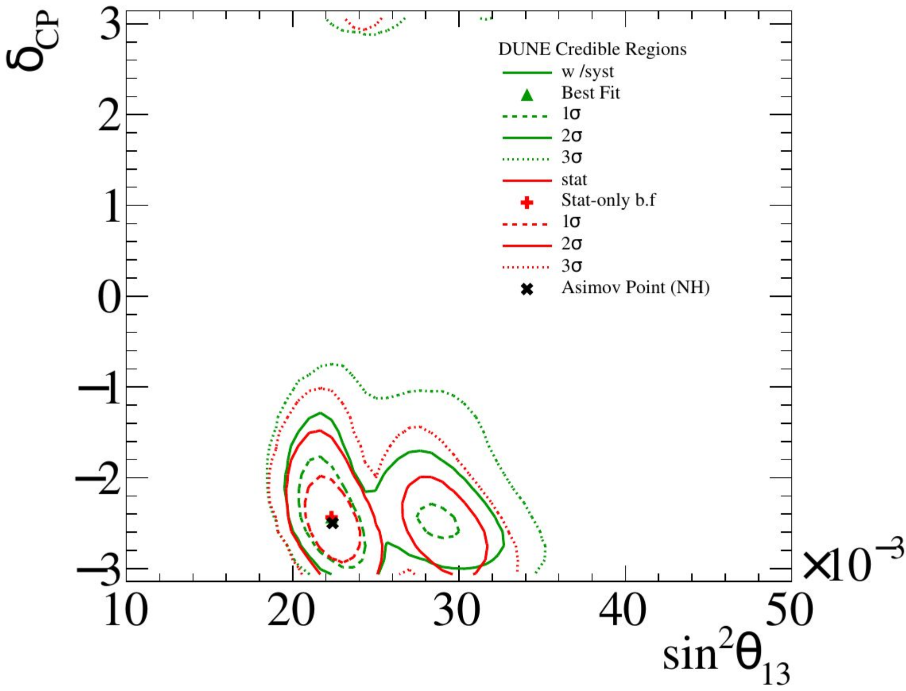


- Best fit point and Asimov point show **good agreement**
- Both θ_{23} octants being evaluated - **correct octant chosen**
- Some degeneracy between θ_{13} and θ_{23}
- **No posterior in IH** as expected

FD-only w/Systs: FD w/Systs Asimov Fit: Stats-only Comparison

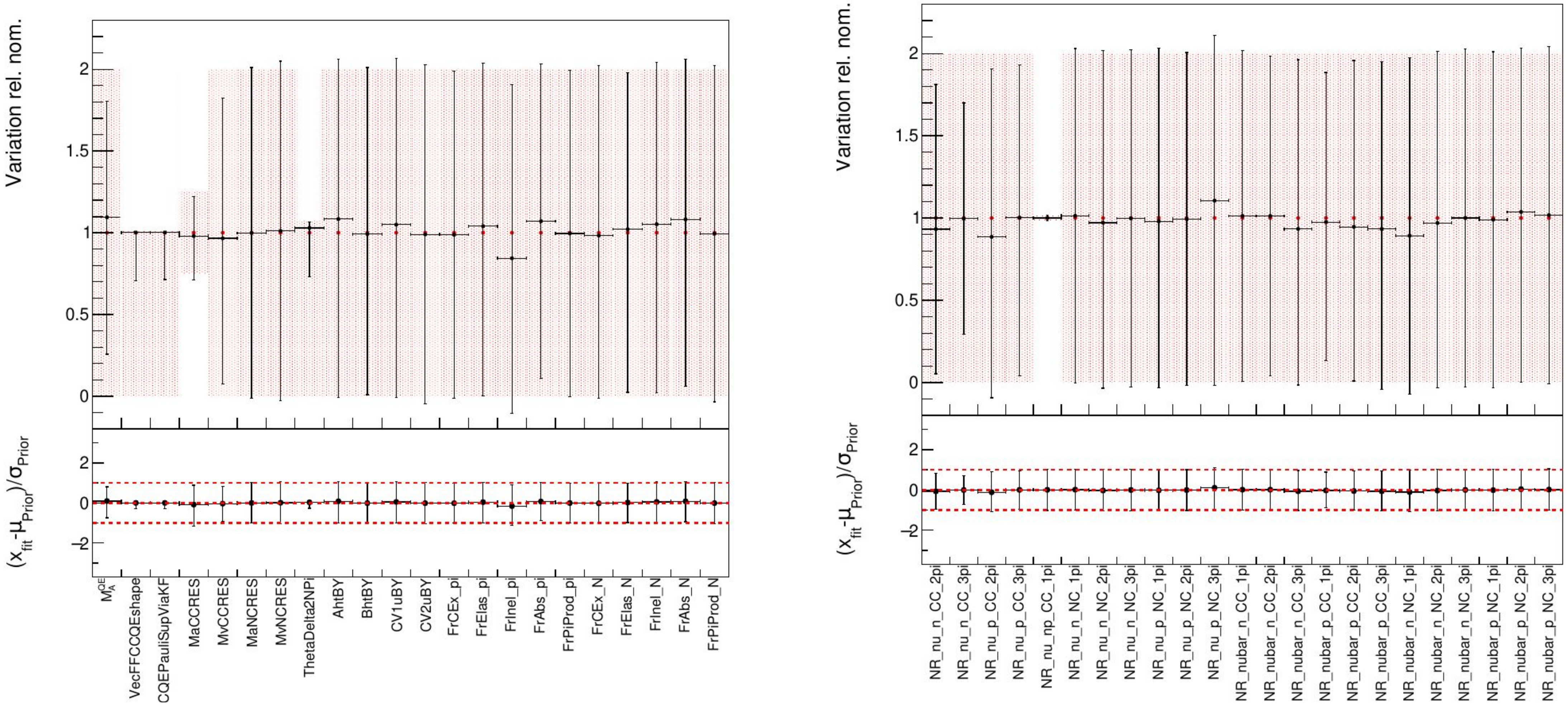






- Contours with systematics are **wider** than stats-only
- Systematics are doing their job!

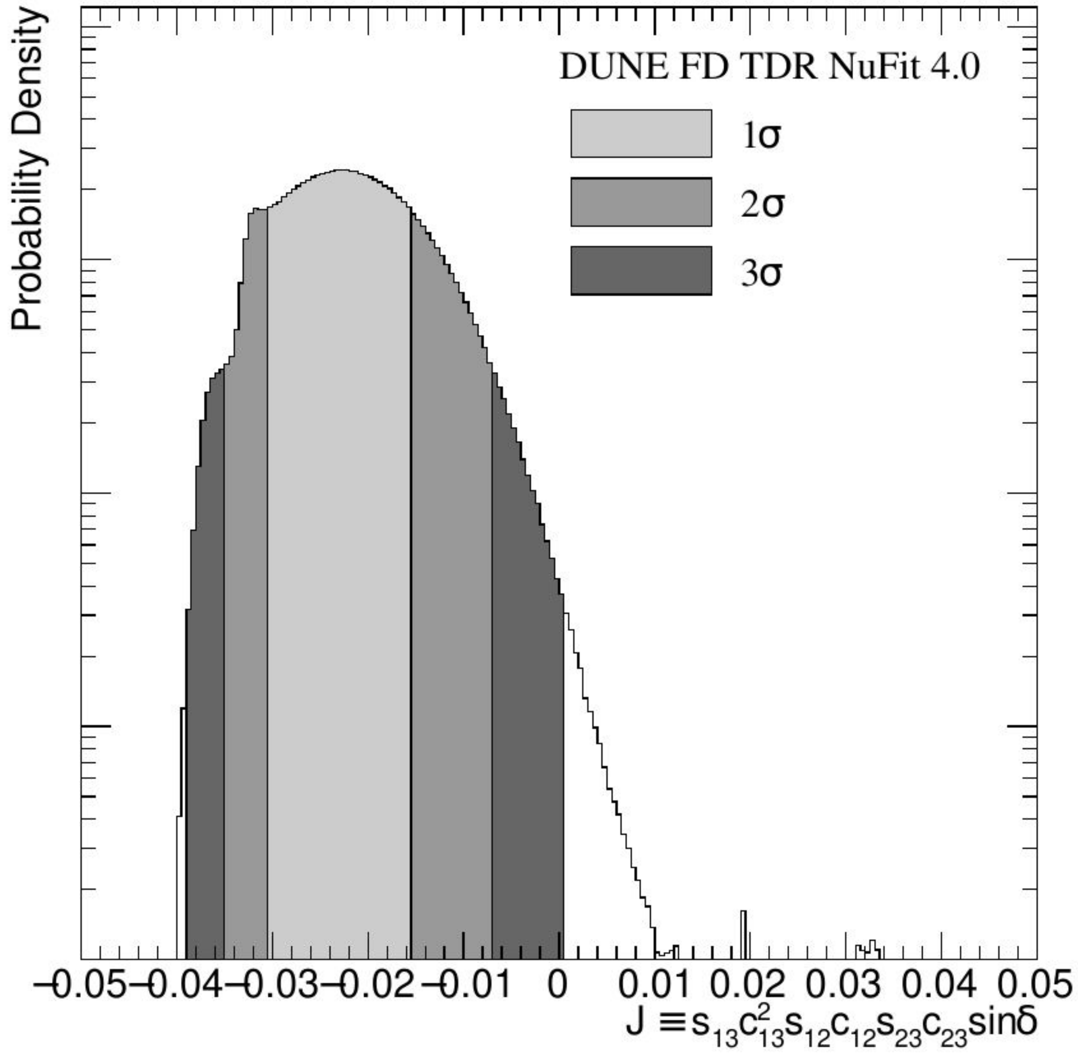
FD w/Systs Asimov Fit: Cross-section Constraints



- **Little constraining power from FD** as expected
- Parameters which appear to have strong constraints have **almost flat priors within bounds**
- Some systematics end up **wider posteriors than priors** -> likely due to correlations with flux

FD w/Systs Asimov Fit: Jarlskog Invariant

- The **Jarlskog invariant** indicates the magnitude of **CP violation**
- Value of 0 indicates **no CP violation**
- MaCh3 can produce a **Jarlskog invariant posterior distribution** without running another fit
- Plan to produce **unitarity triangle plots** -> **Marvin Pfaff (ICL)**



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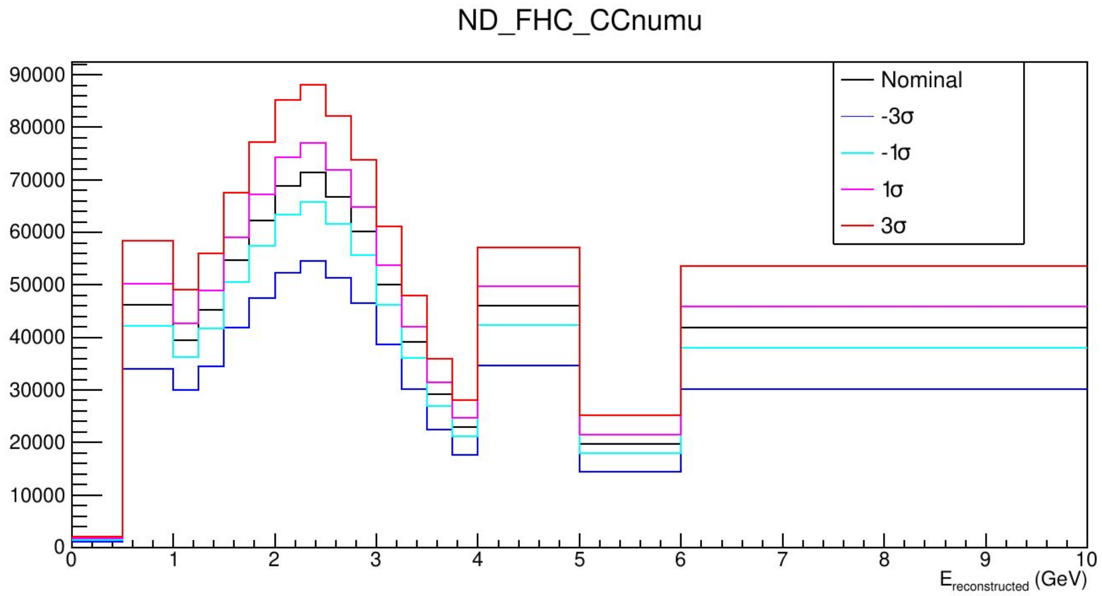
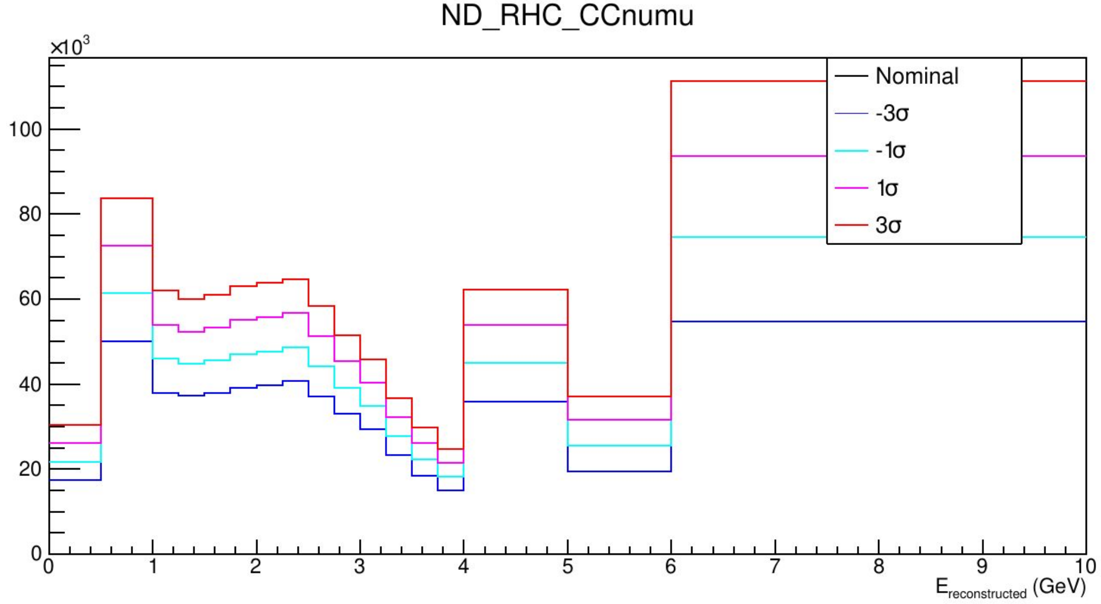
What about ND?

ND Progress

- Added **ND-LAr samples** used in **FD TDR analysis**
- Replicated **FHC CC inclusive** and **RHC CC inclusive** sample cuts
- Produced **varied spectra** on samples with **TDR xsec and flux systematics**
- Produced splines for TDR samples binned in **reco energy**, **true energy** and **Bjorken y**
- Joint **FD + ND fits** running with **xsec and flux systematics** -> chains need to be **tuned**





Conclusion and Plans

- **MaCh3** can perform the **accurate systematic treatment** needed to handle **DUNE's statistics**

- FD-only Asimov fits look as we'd expect
    - Adding **detector systematics -> full FD-only comparison with TDR**

- **ND-LAr samples** added -> xsec + flux fits need **tuning**

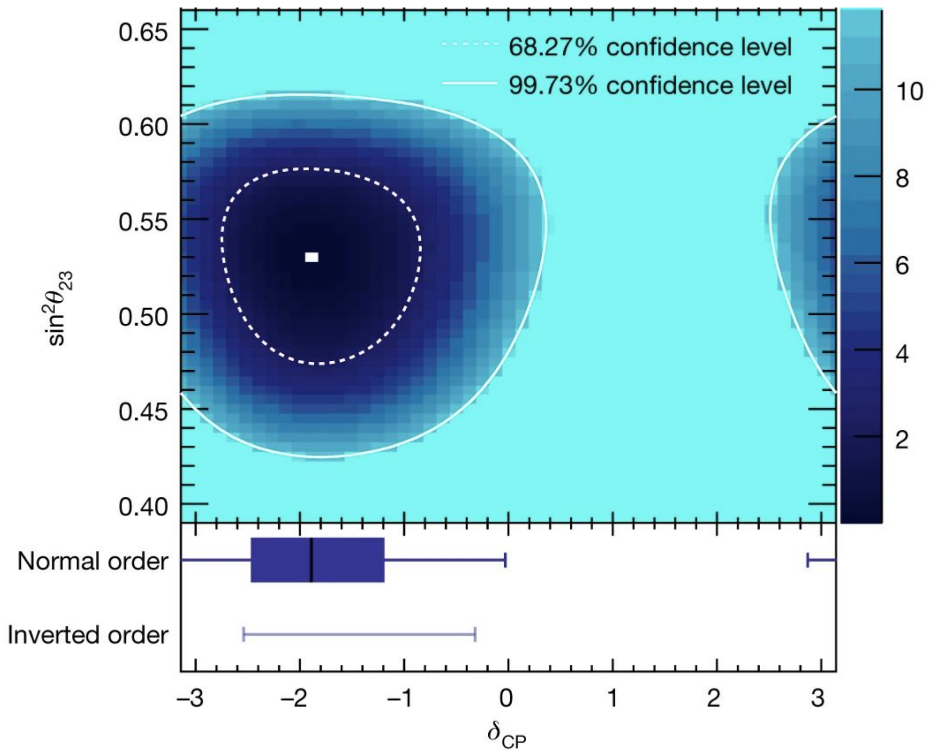
- **UK students** playing a leading role in **DUNE LBL** analysis using **MaCh3**
    - **Naseem Khan (ICL)** will be adding **ND-GAr samples** to this analysis

Back up

And that's MaCh3 in a nutshell…

A Markov Chain Monte Carlo Fitter with a built-in Likelihood Calculator

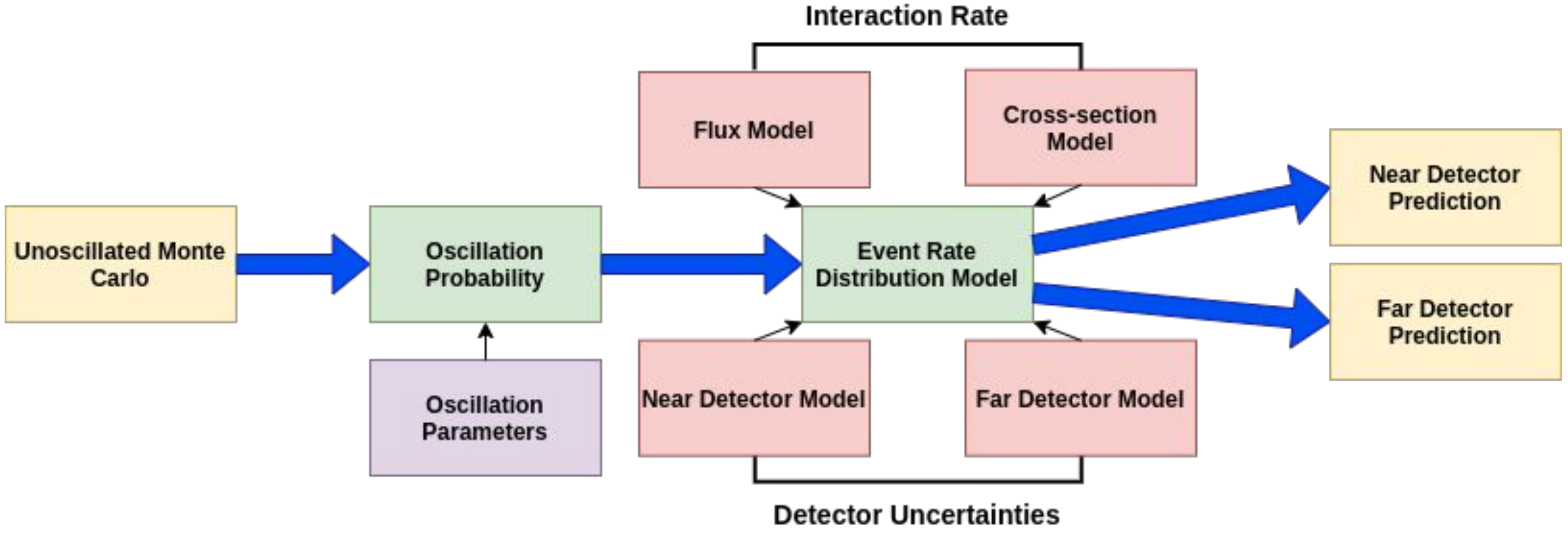
Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations arXiv:1910.03887



Already successfully used on data from **T2K** and **NOvA**, in progress for **DUNE** and **Hyper-K**

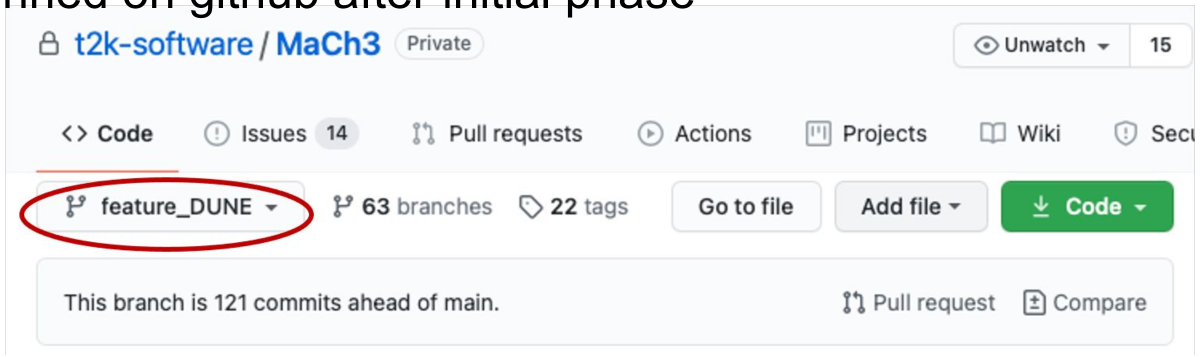
What is MaCh3

- Markov Chain Monte Carlo-based Bayesian fitter with integrated likelihood calculator capable of predicting event rates and distributions at near and far detectors
- Fit distributions at ND and FD to constrain models
- Core functionality is straightforward to adapt to other experiments
- In use for T2K, T2K+NOvA, T2K+SK atmospherics, and in progress for DUNE and Hyper-K
- We usually perform a joint ND+FD fit but can also fit ND separately and use post-ND-fit-constrains in a FD fit



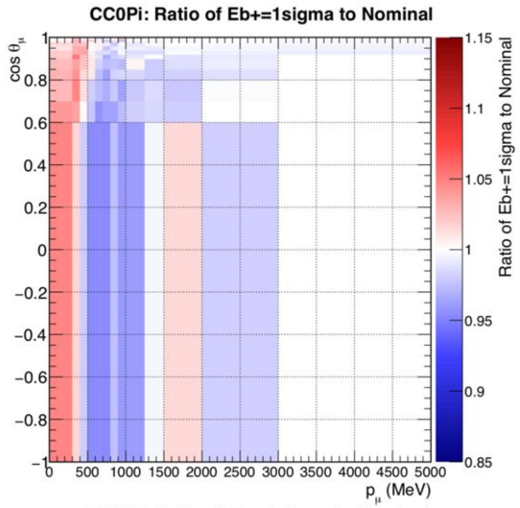
MaCh3 code release

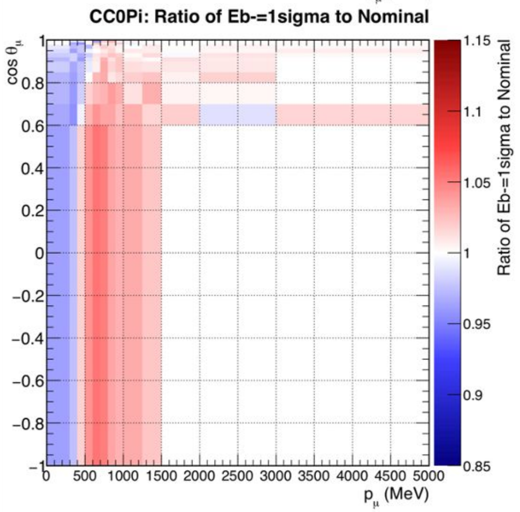
- Code stripped of T2K internal version
  - CPU-only and CPU+GPU versions available
  - Multi-threading
- Using CMake build system, Root 6
- Successfully built at DUNE gpvms, CERN, Royal Holloway, Imperial, ETH, etc. systems
- Release planned on github after initial phase



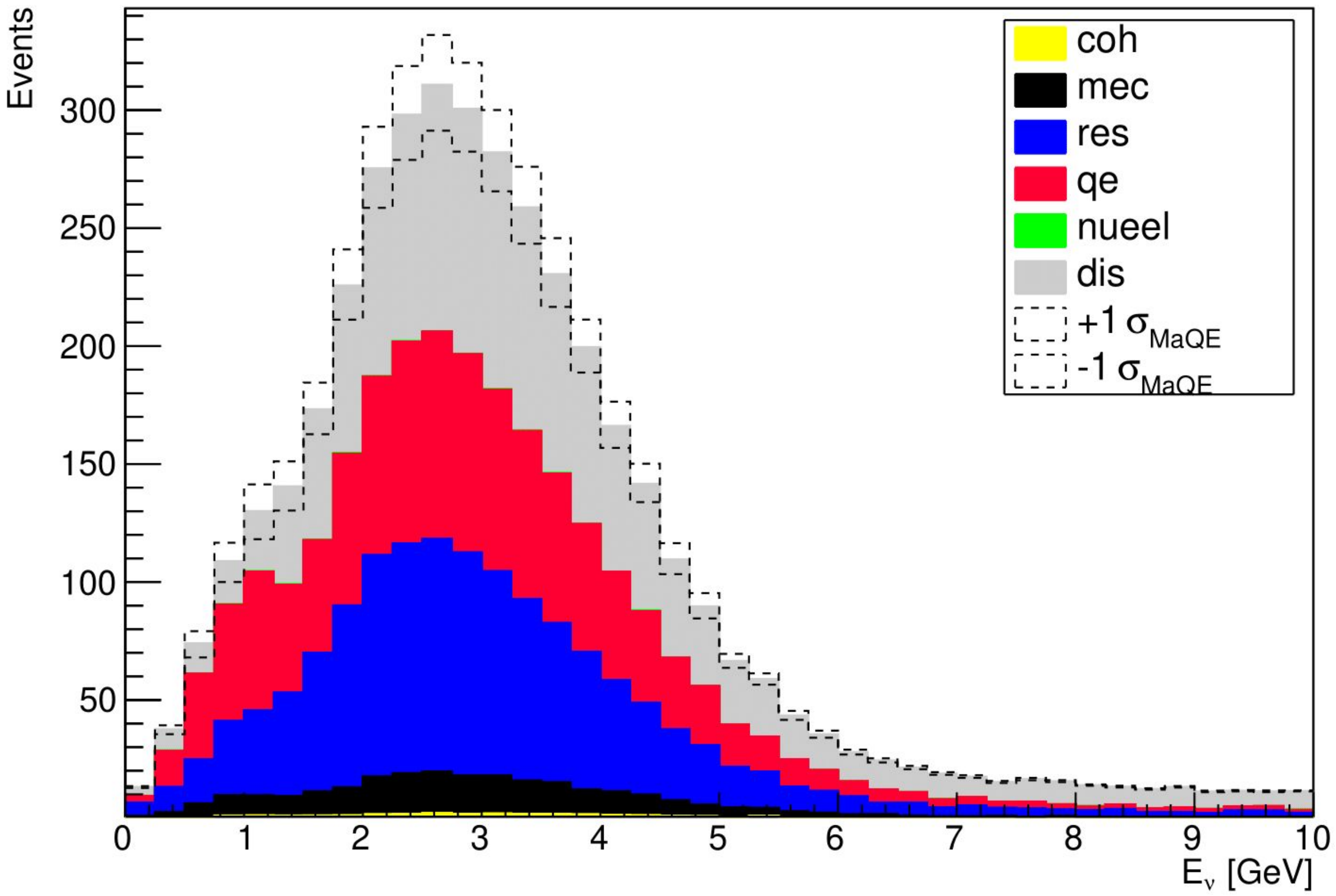
Existing MaCh3 features: reweighting capability

- MaCh3 has full access to event-by-event kinematics during the fit
  - Enables reweights at each parameter step with functional forms on any event variable
  - Also enables shifts of variable at each step, e.g. events can be put in different bins as a result of shift in momentum
- Also infrastructure for standard bin-by-bin response functions and linear normalisations implemented
- Response can be broken down also by interaction mode, oscillation channel, true variable bins, etc.





FHC nue selection per mode
Total variation from MaQE



FD Asimov Fit

- New refactored MaCh3 DUNE **significantly improved step time** allowing us to run longer chains
  - Spline evaluation improvements made in **T2K** reduced step time by ~ **8x!**

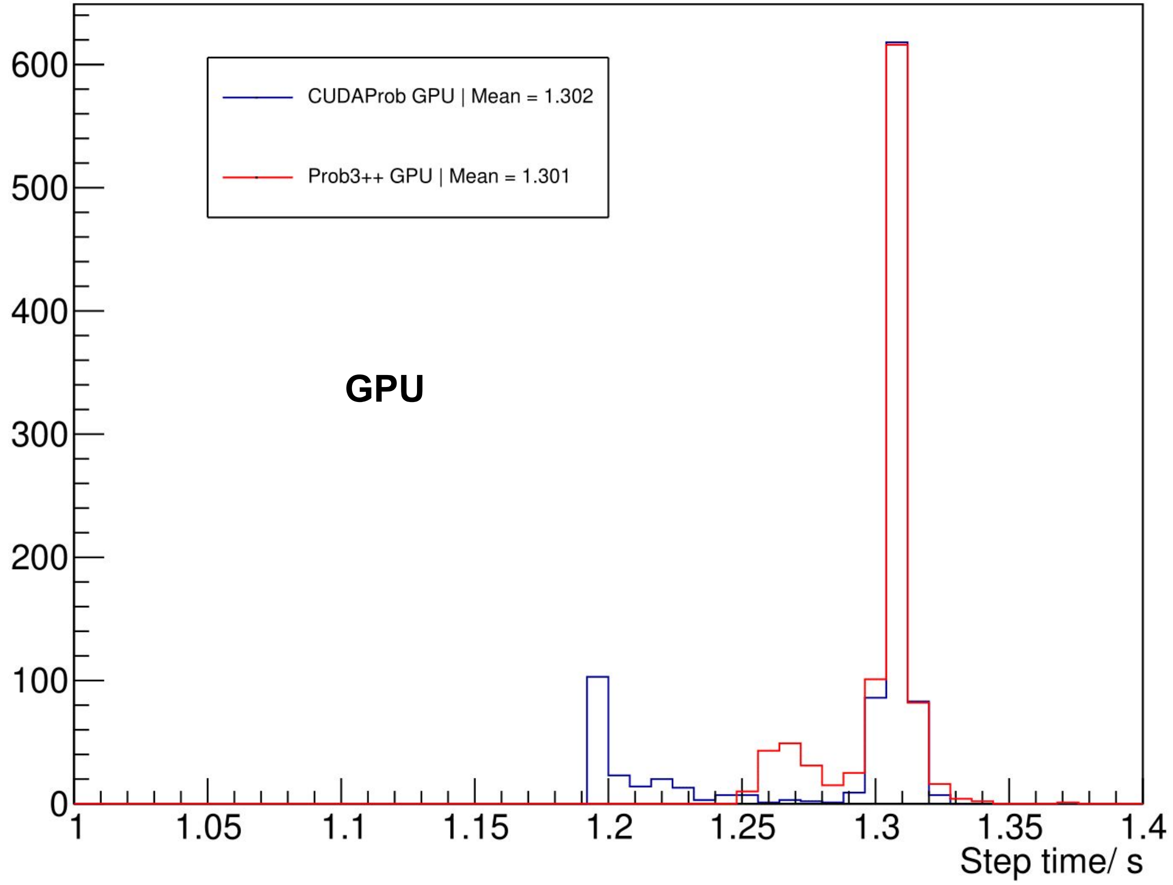
- **Maximal δ_{CP} violation** Asimov point chosen

- Fits were run with **17 million** steps for **stats-only** & **23 million** steps w/ **flux+xsec systs**

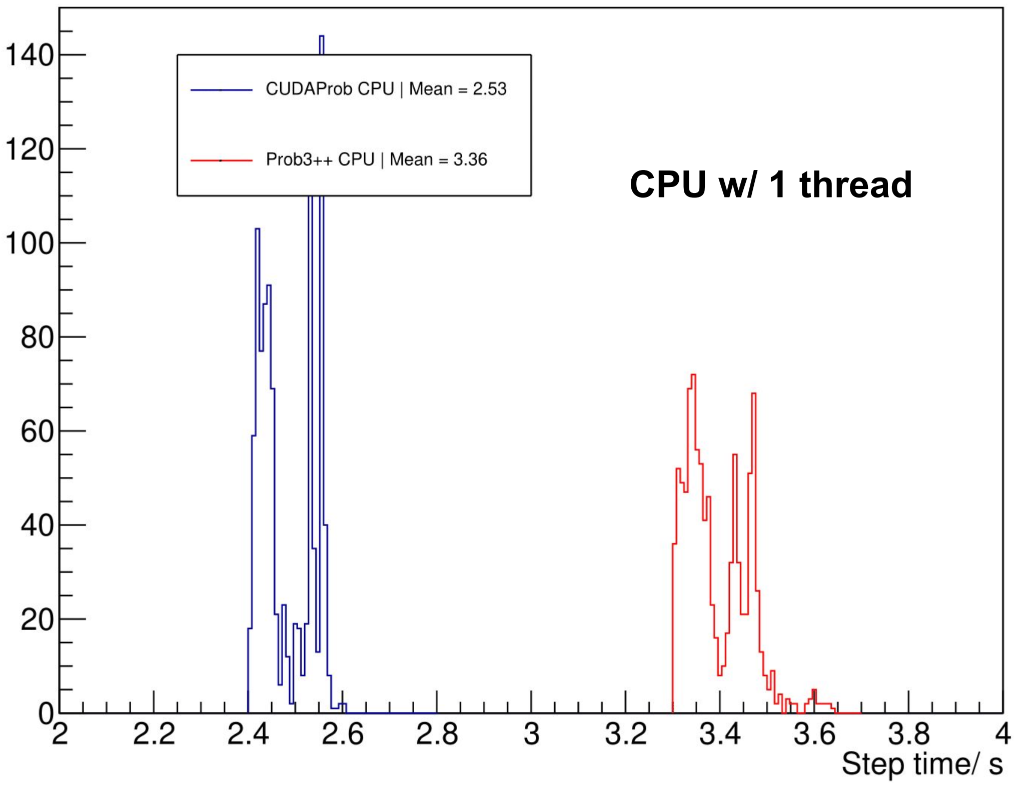
- Typically takes **O(18k)** steps to get an independent step so we have **O(1k) independent points** were evaluated for both

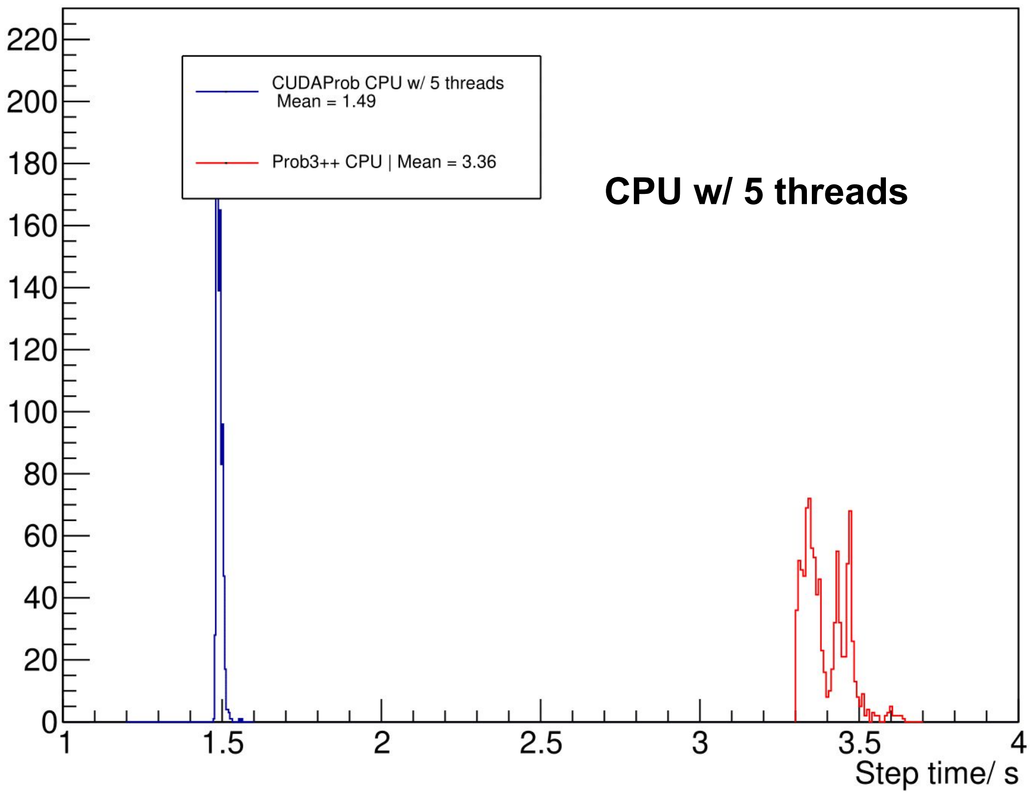
CUDAProb3 Speed

- Checked chain step time by running dummy fits with both **CUDAProb3 and Prob3++** calculators
- GPU step time is **very similar**
- Step time in MaCh3 is generally: **oscillation calculation** + **spline evaluation**
- When using **GPU osc calc** - almost all the steptime is **CPU spline eval**



CUDAProb3 Speed - CPU





- CPU step time improves drastically when osc calc is multi-threaded - **comparable to GPU!**
- CPU osc calc allows us to run **significantly more chains** in **parallel**
- Available to the wider DUNE collaboration!