T2K's MaCh3 Oscillation Analysis

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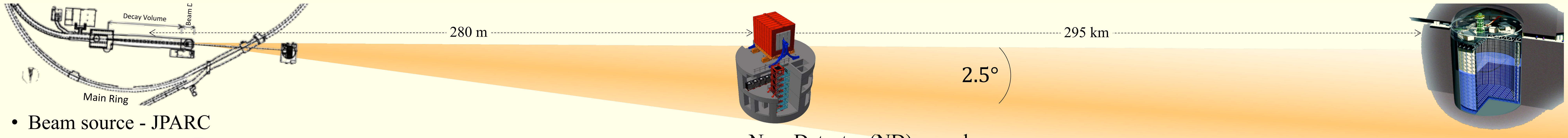
T2K is an off-axis long-baseline neutrino oscillation experiment that aims to measure the neutrino oscillation parameters δ_{CP}, $\sin^2\theta_{13}$, $\sin^2\theta_{23}$, and Δm^2_{32}.



- Beam source - JPARC
  - Produces a ν_μ- or $\overline{\nu}_\mu$-enhanced beam
  - Flux peaks ~0.6 GeV 2.5° off axis, optimizing L/E for maximal disappearance
  - Looking for ν_μ / $\overline{\nu}_\mu$ disappearance and ν_e / $\overline{\nu}_e$ appearance
- Near Detector (ND) complex
  - ND280 – 2.5° off axis
  - INGRID – on axis
- Far Detector (FD) - Super Kamiokande
  - 2.5° off axis
  - 50 kt ultra pure H_2O
  - Water Cherenkov rings from charged particles
  - Walls lined with ~13,000 PMTs

[T2K Collaboration, Nucl. Instrum. Methods A, 659 (2011) 106.]

T2K Bayesian Oscillation Analysis

- Binned likelihood approach:

$$-2\ln\mathcal{L}(\mathbf{a}) = 2\sum_i \left(n_i^{\text{obs}} \ln\left(\frac{n_i^{\text{obs}}}{n_i^{\text{exp}}(\mathbf{a})}\right) - n_i^{\text{obs}} \right) + (\mathbf{a}-\mathbf{a_0})^{\intercal} \boldsymbol{C}^{-1} (\mathbf{a}-\mathbf{a_0})$$

- The covariance matrix $\boldsymbol{C}$ imposes prior constraints on model parameters $\mathbf{a}$ that are used to predict the number of expected events per bin n_i^{exp}.
- $\mathbf{a}$ consists of parameters that govern the neutrino flux, cross section, and oscillation predictions as well as detector responses.
- This poster focuses on the framework of T2K's Bayesian analysis:

Bayes' Theorem

posterior likelihood prior

$$P(\mathbf{a}|D) \propto P(D|\mathbf{a}) \times \pi(\mathbf{a}) = \mathcal{L}(\mathbf{a})$$

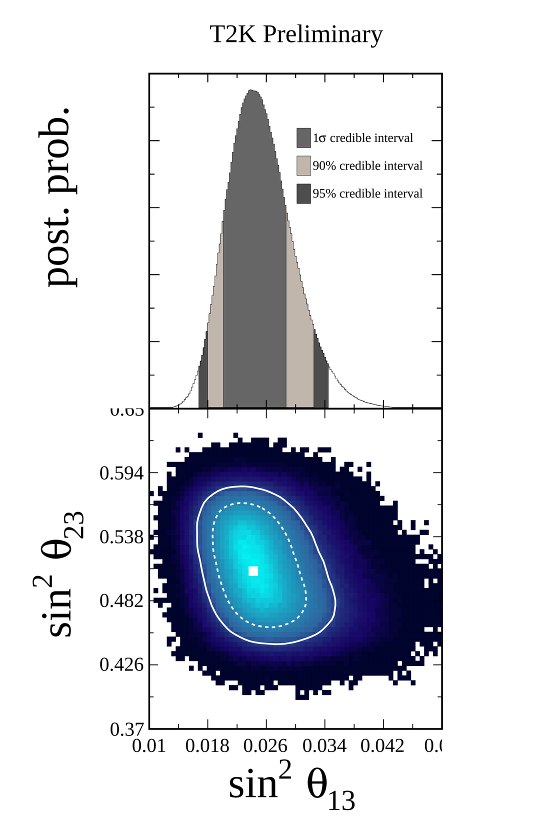
- Credible intervals built from capturing regions of phase space with highest posterior probability.

- Of the ~ 750 parameters in our model, we are only aiming to measure 4 oscillation parameters.

- Marginalize over nuisance parameters opposed to profile. Takes into account non-Gaussianities in higher dimensional posterior distributions.

- Only run the fit once for information on all 750 parameters

- Use Markov Chain Monte Carlo (MCMC) to evaluate the posterior $\mathcal{L}(\mathbf{a})$.



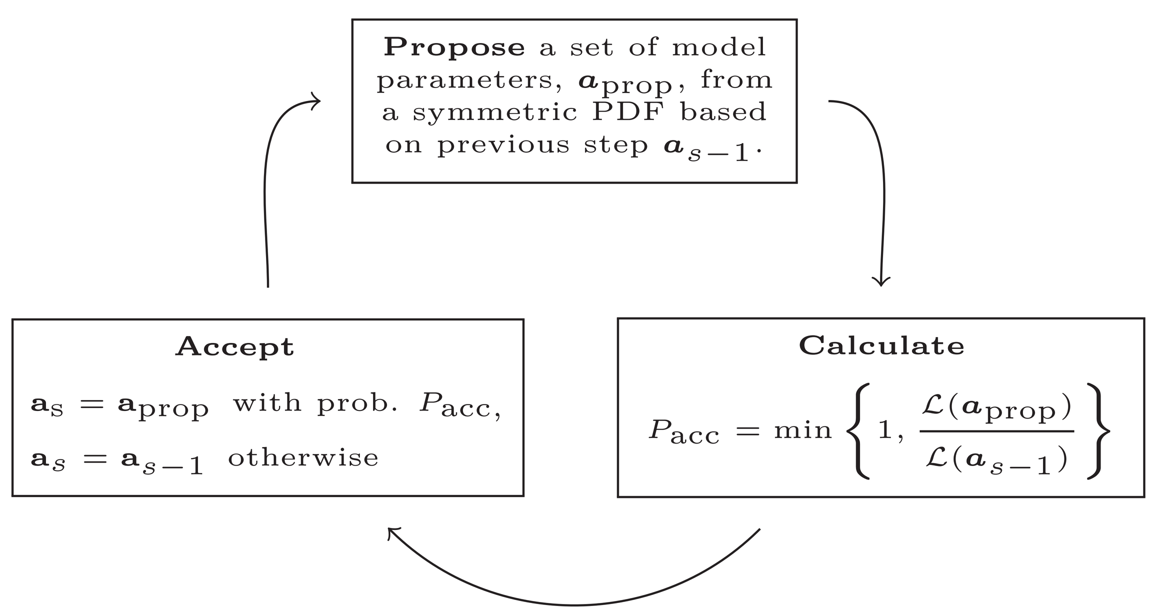
Results shown are from a fit to simulated data.

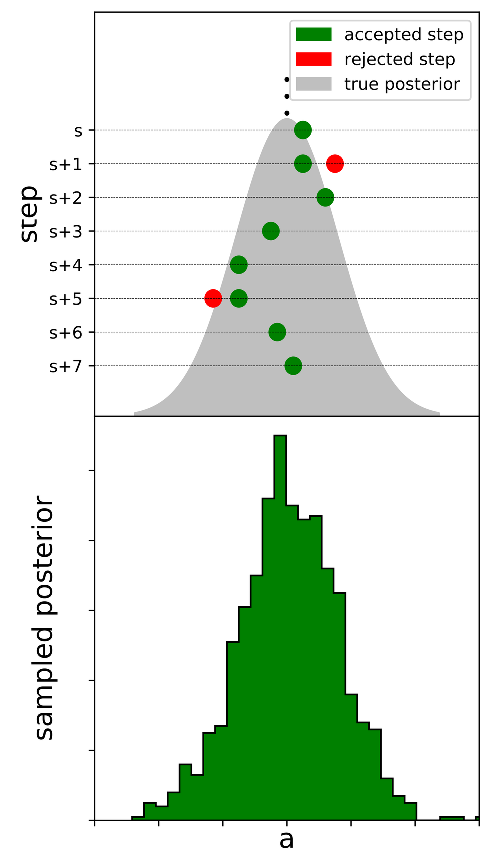
- From the posterior distribution, one can also compare the total posterior probability for different cases against one another.
  - Normal vs. inverted hierarchy
  - Upper vs. lower θ_{23} octant
  - Bayes' Factor: ratio of probabilities between cases

$$BF(NH/IH) = \frac{P(NH)}{P(IH)}$$

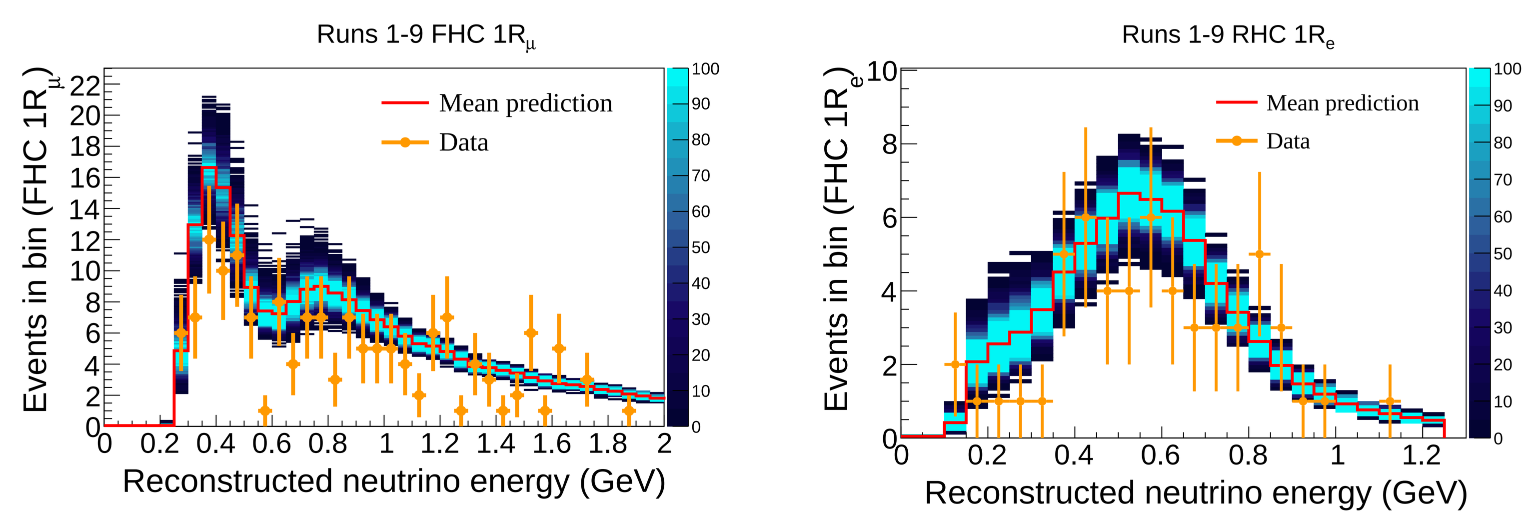
Markov Chain Monte Carlo Fitter

- Applying the Metropolis-Hastings algorithm, which samples the parameter space proportionally to the posterior distribution $\mathcal{L}$:



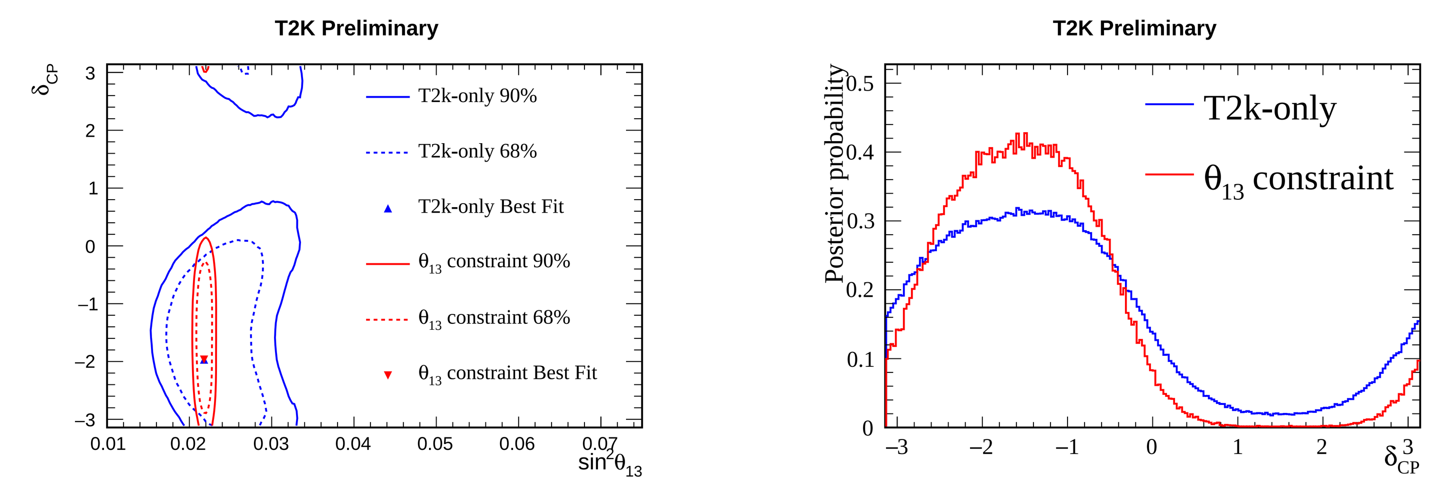


- Evaluating $\mathcal{L}(\mathbf{a})$ for any parameter set $\mathbf{a}$ is the most computationally expensive step.
  - Reweight a nominal prediction with response functions, normalizations, and momentum shifts for selected events.
- Distribution of predicted reconstructed energy spectra from steps of a Markov Chain with fitted data overlayed:



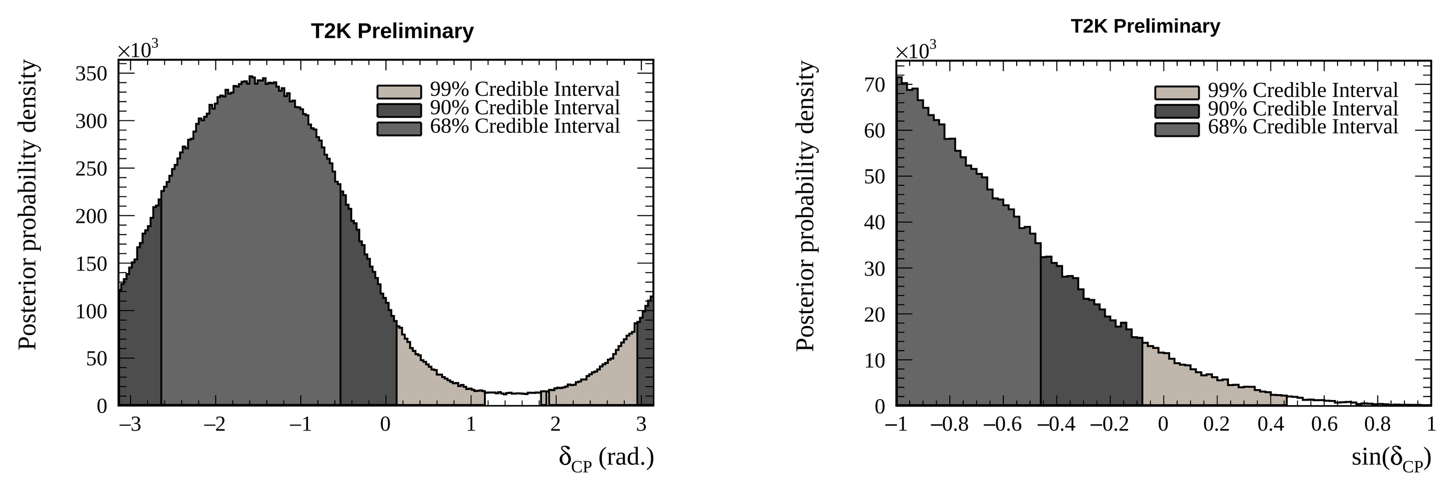
Computational Savings from Posterior Reweighting

- Possible to reweight posterior distributions from MCMC fits in order to apply alternative priors post facto.
  - Mathematically equivalent to rerunning a chain with the new priors.
  - Has saved T2K >30k CPU hours this year.
  - Need to consider the coverage. Generally okay to impose tighter constraints in areas of high probability density.
  - Should avoid weighting up regions of low probability density.
- For example, applying the PDG 2019 world average on θ_{13}, a parameter which reactor experiments have superior sensitivity:



Results shown are from a fit to simulated data.

- Reweight a chain with a flat prior in δ_{CP} to correspond to one run with a flat prior on $\sin(\delta_{CP})$:



Results shown are from a fit to simulated data.

T2K has made significant model improvements and added 34% more neutrino mode data since the last release. See P. Dunne's talk for latest results!