3-flavour results with NOvA

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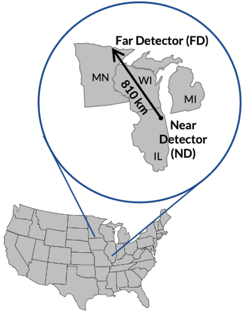
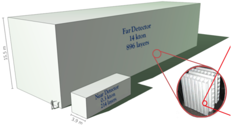
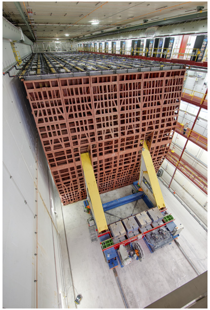
NOvA

- Long baseline neutrino accelerator experiment
- A beam of neutrinos is produced in Fermilab
- The Near Detector is 1 km away from the source. 100 m underground, shielded against cosmic rays
- The Far Detector is 810 km away from the source and 14 mrad off axis, in Minnesota. On the surface, high rate of cosmic rays





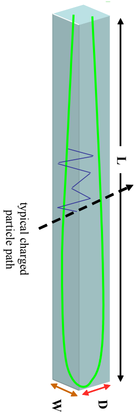
Near Detector

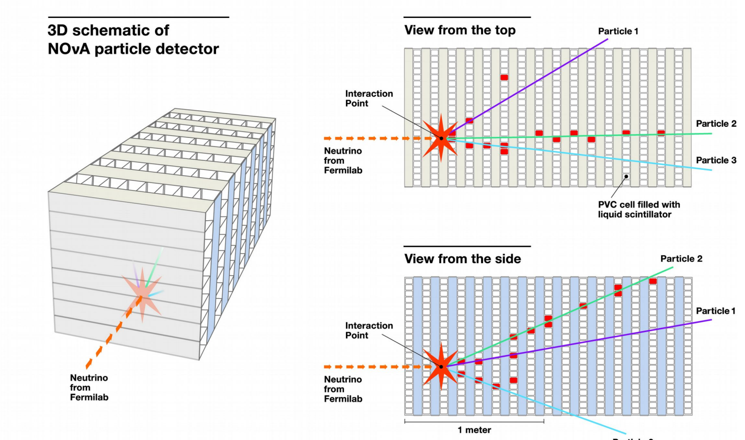


Far Detector

NOvA

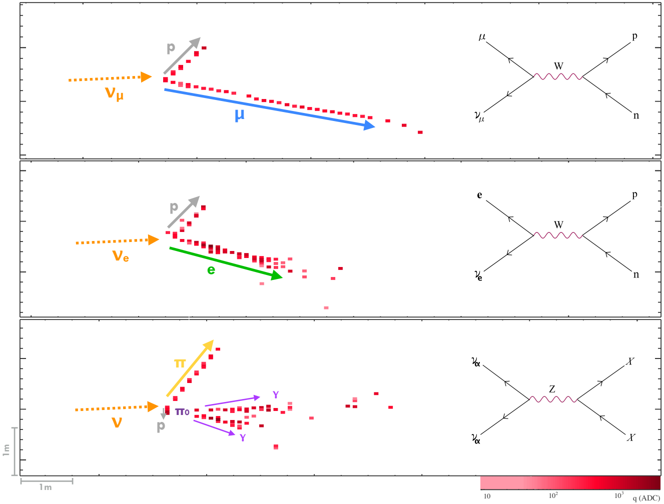
- Calorimetric, liquid scintillator detector
- The cells have horizontal and vertical orientation in each plane allowing for 3D reconstruction
- There is a fibre inside each cell that carries the light to the readout



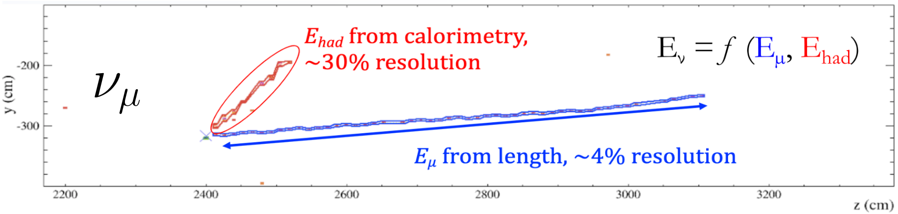


Identifying events and particles

- For 3-flavour analyses, a Convolutional Neural Network (CNN) is used to identify particles
- Calibrated hits (with cosmic muons) are provided as pixel maps
- The network classifies these events in several signal and background categories
- Neutrino and antineutrino modes are trained independently



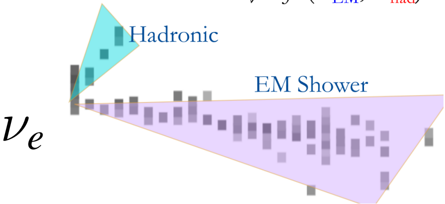
Neutrino energy estimation



- Energy estimated from muon length and hadronic shower

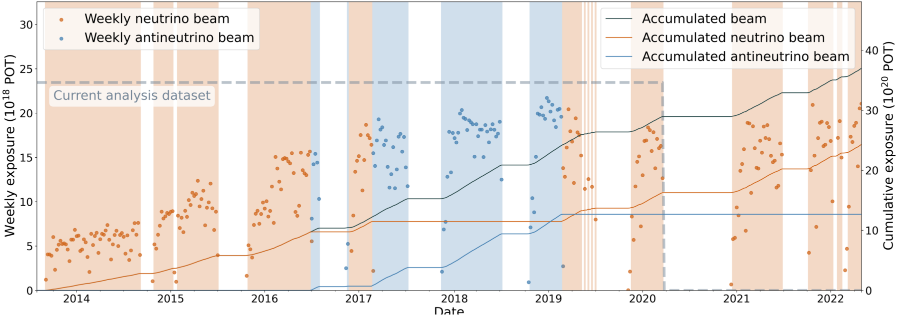
$E_\nu = f\,(E_{EM}, E_{had})$

- Energy estimated from the electromagnetic shower and hadronic component



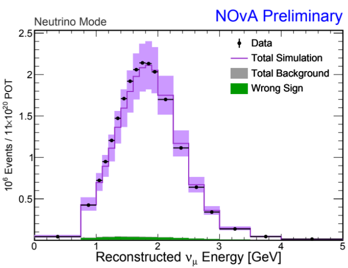
The sample: POT

- Exposure is measured in Protons On Target (POT), the number of protons that collided with the target
- $13.6 \cdot 10^{20}$ POT in neutrino mode
- $12.5 \cdot 10^{20}$ POT in antineutrino mode

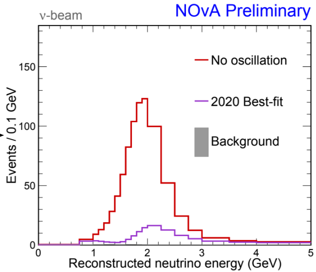


Making predictions

- To make predictions first we have to
  - **Detect** the neutrino event
  - **Identify** the particles
  - **Reconstruct** its energy
- The predictions for the FD are obtained from the ND: **extrapolation**



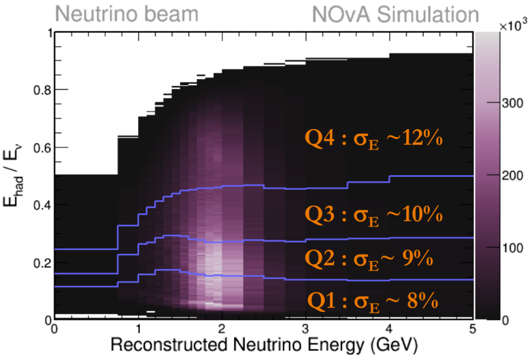
Near Detector

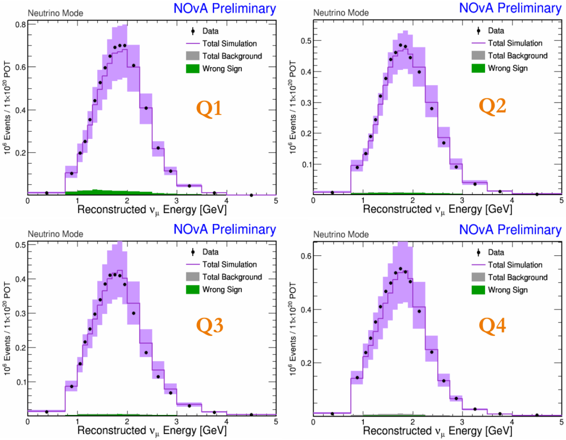


Far Detector

The ν_μ sample: Hadronic energy quartiles

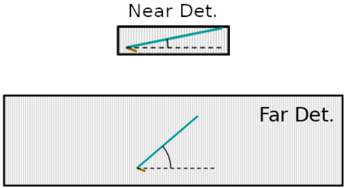
- Oscillation sensitivity depends on the shape of the spectrum
- By separating in fraction of hadronic energy, high and low resolution events are separated increasing the sensitivity to the oscillation dip

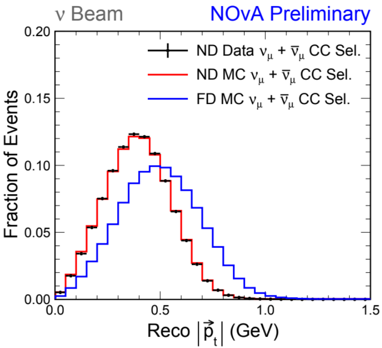




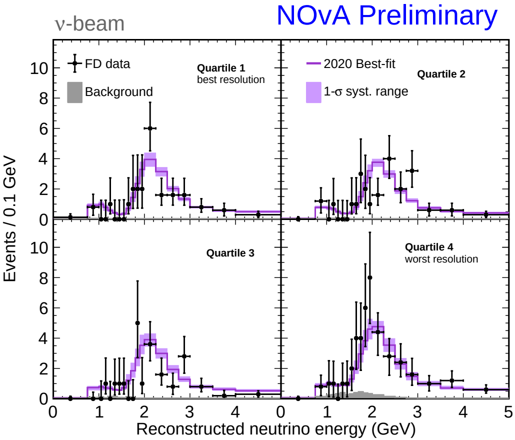
The ν_μ sample: p_t extrapolation

- Detector acceptance is different in the transverse direction for the ND and FD because of their different size
- Bins of p_t are made to better match samples between the ND and FD and increase oscillation sensitivity

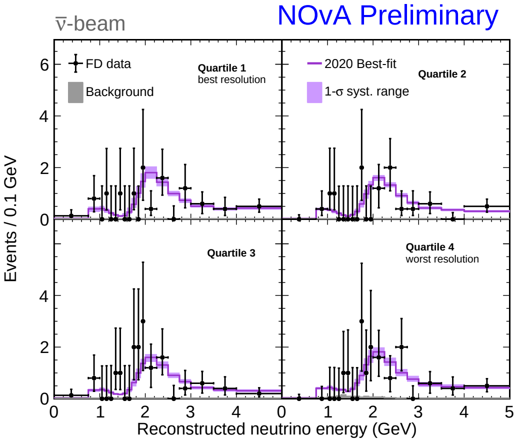




The ν_μ sample

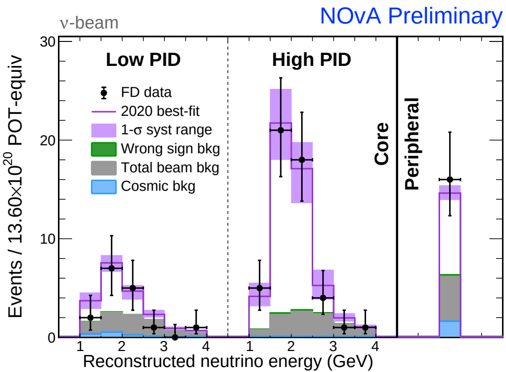


211 events with 8.2 background

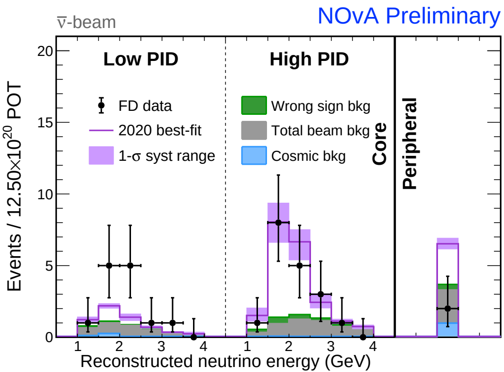


105 events with 2.1 background

The ν_e sample



82 events observed



33 events observed (4σ)

Bayes Theorem

$$\underbrace{P(\vec{\theta}|\vec{x})}_{\text{Posterior}} = \frac{\overbrace{P(\vec{x}|\vec{\theta})}^{\text{Likelihood}} \cdot \overbrace{P(\vec{\theta})}^{\text{Prior}}}{\underbrace{P(\vec{x})}_{\text{Evidence}}}$$

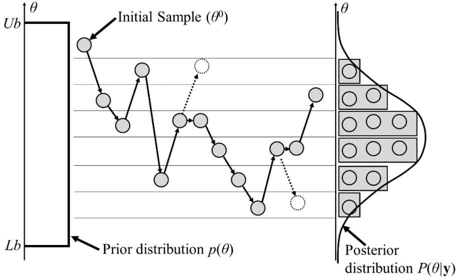
- Credible intervals or regions (regions where the posterior is maximized)
- Posterior depends on the choice of prior, uninformative (i.e. constant) prior typically chosen
- Likelihood: binned Poisson likelihood (same as in the frequentist analysis)

$$\ln P(\vec{x}|\vec{\theta}) = -2 \sum_{i=1}^{N} \left[E_i(\vec{\theta}) - O_i + O_i \ln \frac{O_i}{E_i(\vec{\theta})} \right]$$

- Nuisance parameters (due to systematics) are marginalized (integrated)

Markov Chain Monte Carlo (MCMC)

- One way of aproximating the posterior by using a Monte Carlo sampling method
- Iterative process: at each iteration parameters are deviated and the new values can be accepted or be rejected (duplicating the previous value in the chain)
- The result is a series of values whose distribution approximates the posterior



- Two methods implemented in the CAFAna fitting framework in NOvA:
  - Metropolis-Hastings
  - Hamiltonian MCMC

Markov Chain Monte Carlo (MCMC)

- **Metropolis-Hastings**
- Proposal function: gaussian, Σ is the step size, needs tuning

$$g(\vec{\theta}'|\vec{\theta}) = (2\pi)^{-\frac{N}{2}} (\det \Sigma)^{-\frac{1}{2}} \exp\left(-\frac{1}{2}\left(\vec{\theta}' - \vec{\theta}\right)^T \Sigma^{-1} \left(\vec{\theta}' - \vec{\theta}\right)\right) \tag{1}$$

- Acceptance function, this is where the likelihood is included

$$A(\vec{\theta}, \vec{\theta}') = \min\left(1, \frac{P(\vec{\theta}'|\vec{\theta})}{P(\vec{\theta}|\vec{\theta}')} \frac{g(\vec{\theta}|\vec{\theta}')}{g(\vec{\theta}'|\vec{\theta})}\right) \tag{2}$$

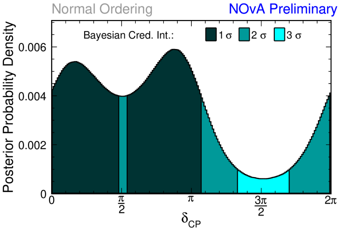
- Draw next sample from (1) and then decide whether to accept or reject based on (2)
- **Hamiltonian MCMC**: Add momentum to the minimization ($H = -\log P(\vec{\theta}|\vec{x})$)

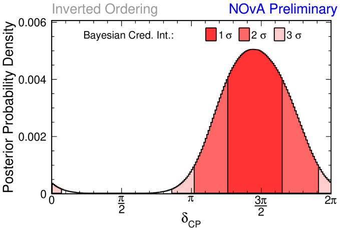
$$\frac{d\vec{q}}{dt} = \frac{\partial H}{\partial \vec{p}} = \frac{\partial T}{\partial \vec{p}}$$

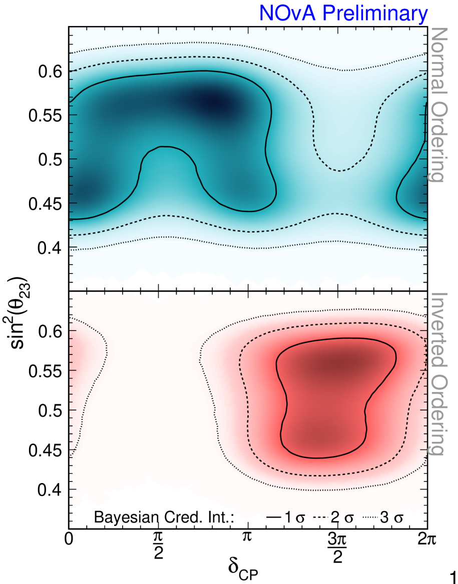
$$\frac{d\vec{p}}{dt} = -\frac{\partial H}{\partial \vec{q}} = -\frac{\partial T}{\partial \vec{q}} - \frac{\partial V}{\partial \vec{q}}$$

$$T(\vec{q}, \vec{p}) = \frac{1}{2}\vec{p}^T M^{-1} \vec{p} + \log|M| + \text{const}$$

Bayesian Results: $\delta_{\rm CP}$ and $\sin^2\theta_{23}$

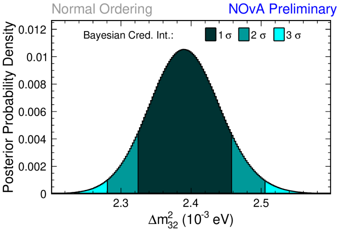


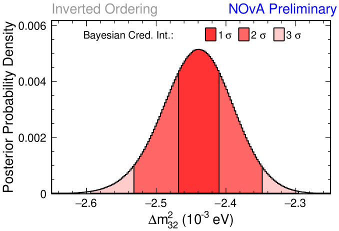




- θ_{13} from PDG 2019
- Conclusions unchanged from the 2020 analysis:
  - $\delta_{\rm CP} = \frac{3\pi}{2}$ not preferred at the 2σ level (NO)
  - $\delta_{\rm CP} = \frac{\pi}{2}$ excluded at 3σ (IO)
  - Upper octant of θ_{23} preferred

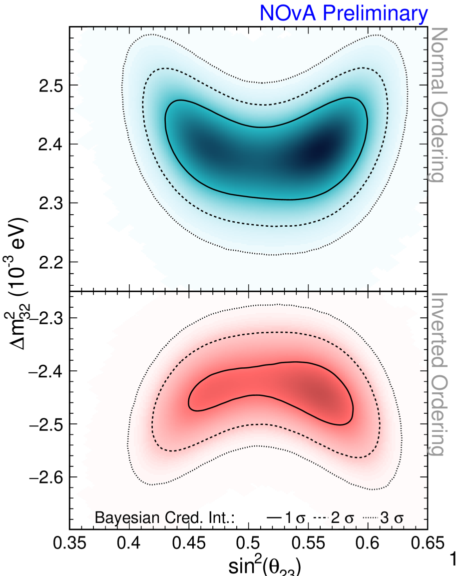
Bayesian Results: Δm^2_{32}





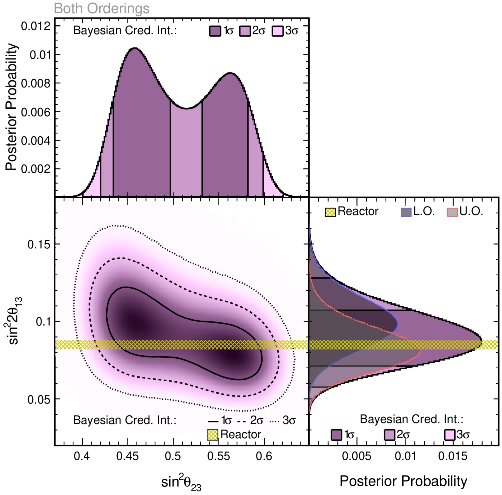
- Slightly prefer upper octant (bayes factor 2.1)
- Slightly prefer normal mass ordering (bayes factor 1.7)

	N. Ordering	I. Ordering	
U. Octant	41.7%	20.9%	62.6%
L. Octant	25.8%	11.5%	37.4%
	67.5%	32.5%	



Bayesian Results: $\sin^2 2\theta_{13}$

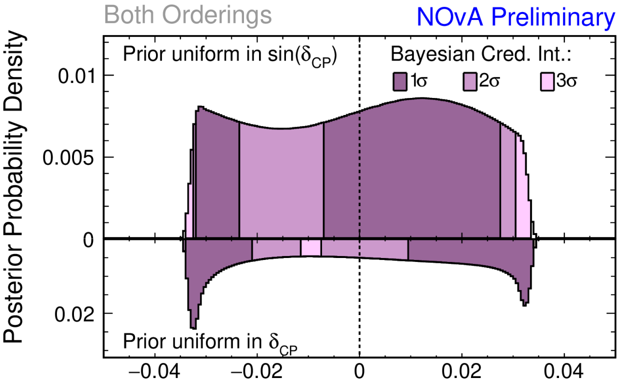
- Typically θ_{13} is used to constrain the fit. In this case it is measured by NOvA
- Larger θ_{13} favour the lower octant and small θ_{13} favour lower octant
- Results agree with reactor experiments
- $\sin^2 2\theta_{13} = 0.085^{+0.020}_{-0.016}$



Jarlskog Invariant

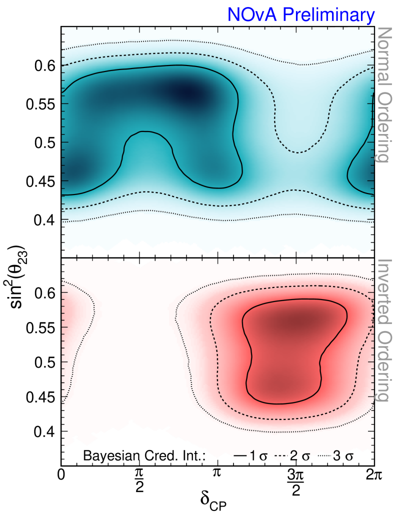
$$J = c_{12}c_{13}^2c_{23}s_{12}s_{13}s_{23}\sin\delta_{\text{CP}}$$

- Measure of CP violation independent of the parameterization
- Prior flat in $\sin\delta_{\text{CP}}$ at the top and flat in δ_{CP} at the bottom

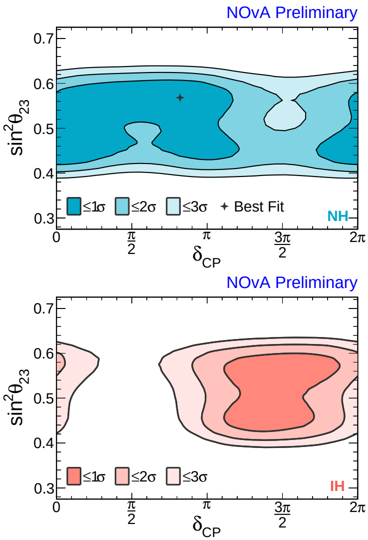


Comparison: Bayesian and Frequentist

Bayesian



Frequentist



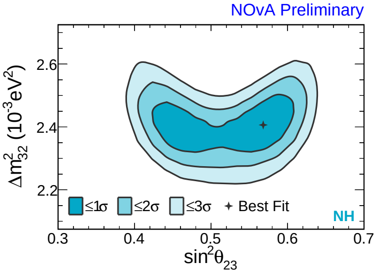
Frequentist Results: $\sin^2\theta_{23}$ results

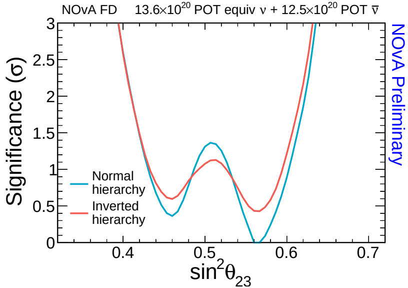
Best fit

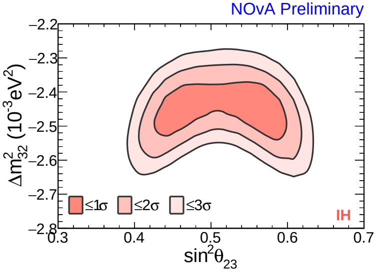
$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$

$\Delta m^2_{32} = (+2.41 \pm 0.07) \cdot 10^{-3}$ eV^2

- Maximal mixing disfavoured at 1.1σ
- Upper Octant is preferred at 1.2σ

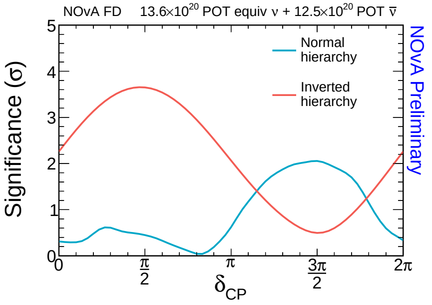


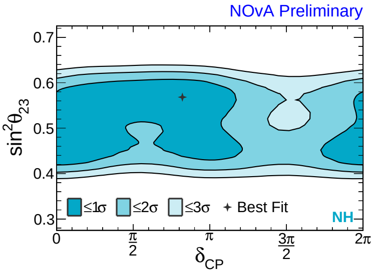


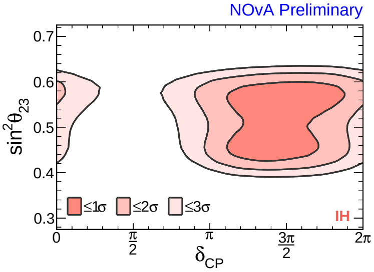


Frequentists Results: δ_{CP} results

- Excludes $\delta_{CP} = \frac{\pi}{2}$ at $> 3\sigma$ in IH and $\delta_{CP} = \frac{3\pi}{2}$ at $\sim 2\sigma$ in NH
- Normal hierarchy preferred at 1σ





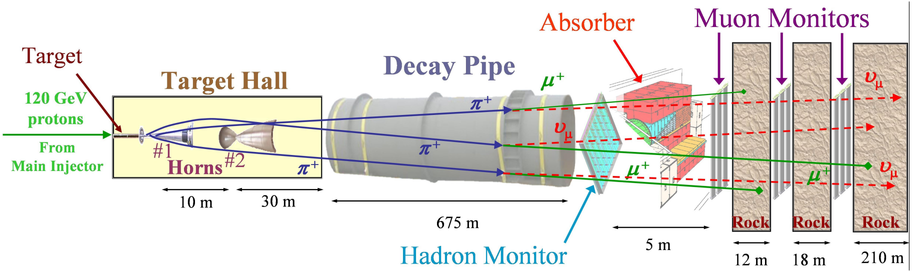


Summary

- New Bayesian fit to study NOvA data, deeper look into the data
- Results agree with the frequentist fit: $\delta_{\mathrm{CP}} = \frac{\pi}{2}$ rejected at 3 sigma, slight preference for the upper octant and normal mass ordering
- First measurement of θ_{13} by NOvA
- New results later this year (NOvA - T2K fit)

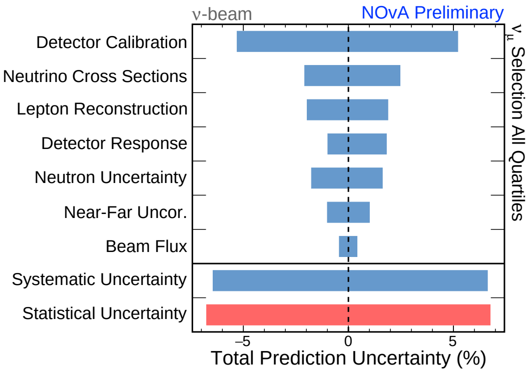
Backup

The Beam



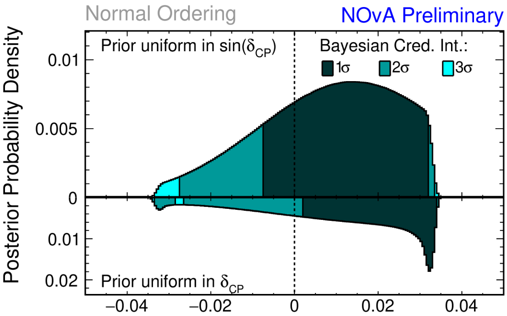
- 120 GeV protons collide with a graphite target
- Magnetic horns are used to focus charged pions
- Pions decay in the decay pipe, producing muon neutrinos or antineutrinos
- Muon monitors allow us to study the beam, for example beam alignment

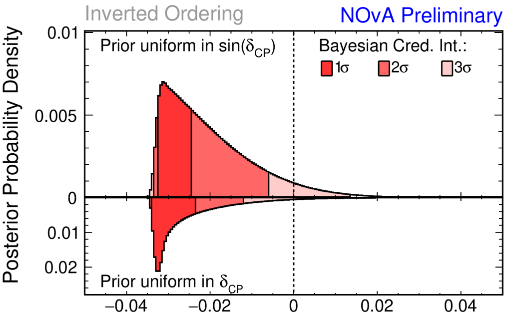
Uncertainties



- Systematic uncertainties dominated by calibration and energy scale

Jarlskog invariant





Comparison: NOvA and T2K