MaCh3 on T2HK

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Neutrino Oscillations

- Neutrino mass and weak eigenstates are decoupled; this results in distance/energy dependent weak flavour oscillations [1].
- The probability of a neutrino weak flavour state, ν_α, oscillating into a state, ν_β, at energy E and over a distance L is given by [2]

$$p(\nu_\alpha \rightarrow \nu_\beta) = \left| U_{i\alpha}^{*} \sum_i U_{\beta i} e^{-i m_i^2 \frac{E}{L}} \right|^2$$

- The transition operator, U, is unitary and known as the PMNS matrix. For 3 neutrino flavours it can be parametrised in terms of 3 real angles $(\theta_{13}, \theta_{23}, \theta_{12})$ and a complex phase (δ_{cp}).
- Due to the difficulty in measuring neutrinos, there are several unknown properties. Among them are:
  - CP violation; If $\delta_{cp} \neq \{k\pi : k \in \mathbb{Z}\}$, neutrino and anti-neutrino oscillation probabilities will differ thus violating CP symmetry.
  - Neutrino Mass Hierarchy: Neutrino masses cannot be measured directly and can only be observed through $m_{ij}^2 = m_i^2 - m_j^2$. This results in a degeneracy whereby it's unclear if $m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$.

T2HK

- Next generation long baseline neutrino oscillation experiment and upgrade to the currently running T2K experiment [3].
- Upgrades + improvements include:
  - Order of magnitude increase in beam flux and expected number of ν events [Fig. 1].
  - Near detector is receiving several upgrades to sensitivity.
  - Addition of an intermediate water Cherenkov detector (IWCD).
  - New far detector (Hyper-K) will be used with ~8.31 times the fiducial volume of Super-K.
  - Aims to provide higher precision measurement of several oscillation parameters.

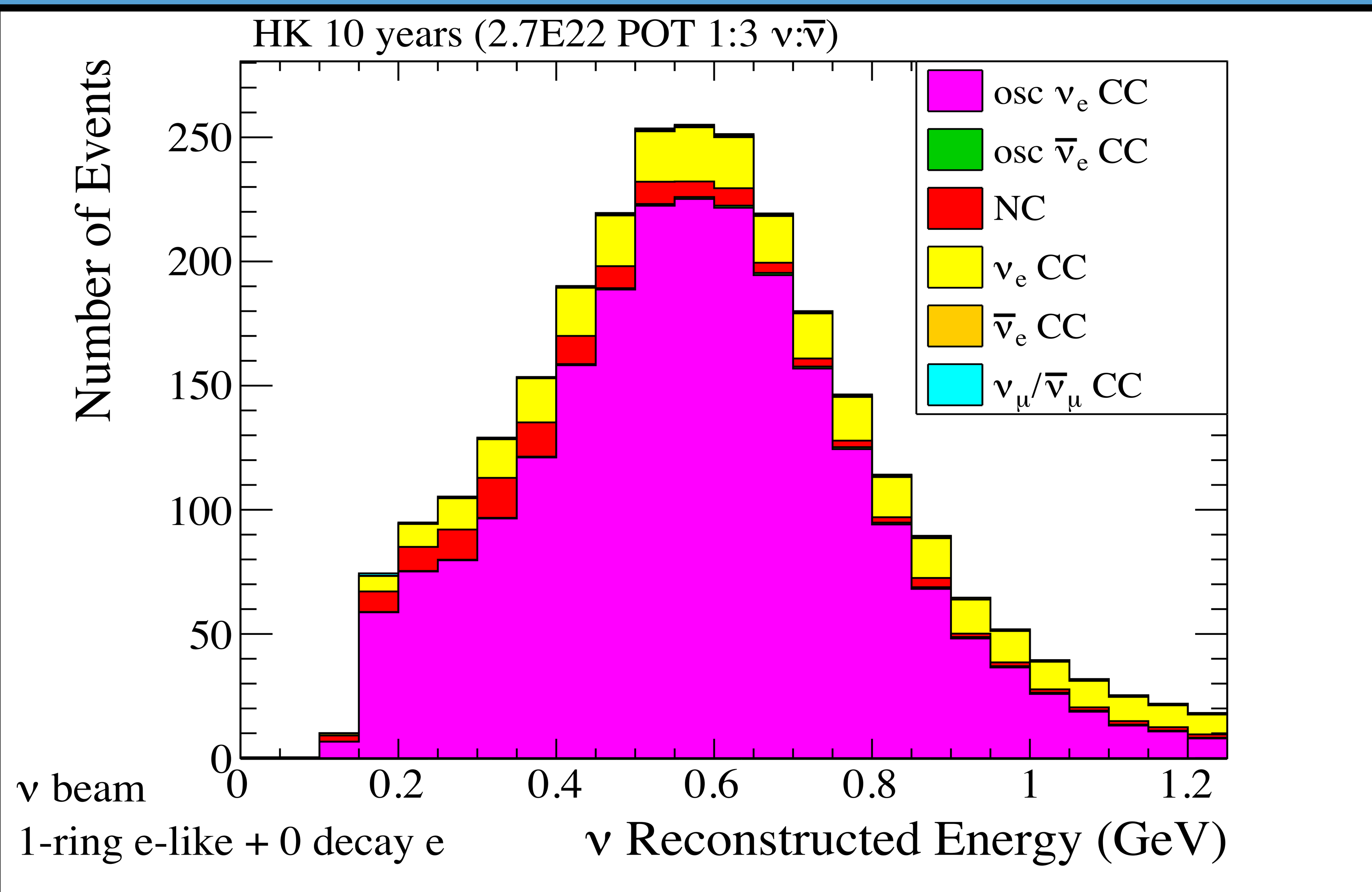

Fig 1 : Predicted distribution of single ring electron-like events in HK

References :
[1] Z. Maki, M. Nakagawa, and S. Sakata, "Remarks on the Unified Model of Elementary Particles," Progress of Theoretical Physics, 1962
[2] K. Zuber, Neutrino physics. CRC press, 2020
[3] H.-K. Proto-Collaboration, K. Abe, et al., "Hyper-Kamiokande design report," 2018

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A Brief introduction to MaCh3

- MaCh3 performs a Bayesian fit on neutrino oscillation data for several planned and currently running experiments (T2K, NOνA, DUNE, HK and more!) using Metropolis-Hastings Markov chain Monte Carlo (MCMC).
- MCMC is analogous to a random walk around a PDF and is more efficient than standard MC for high dimensional spaces.
- MaCh3 uses a binned log-likelihood approach, summing over binned LLHs for each fit component.

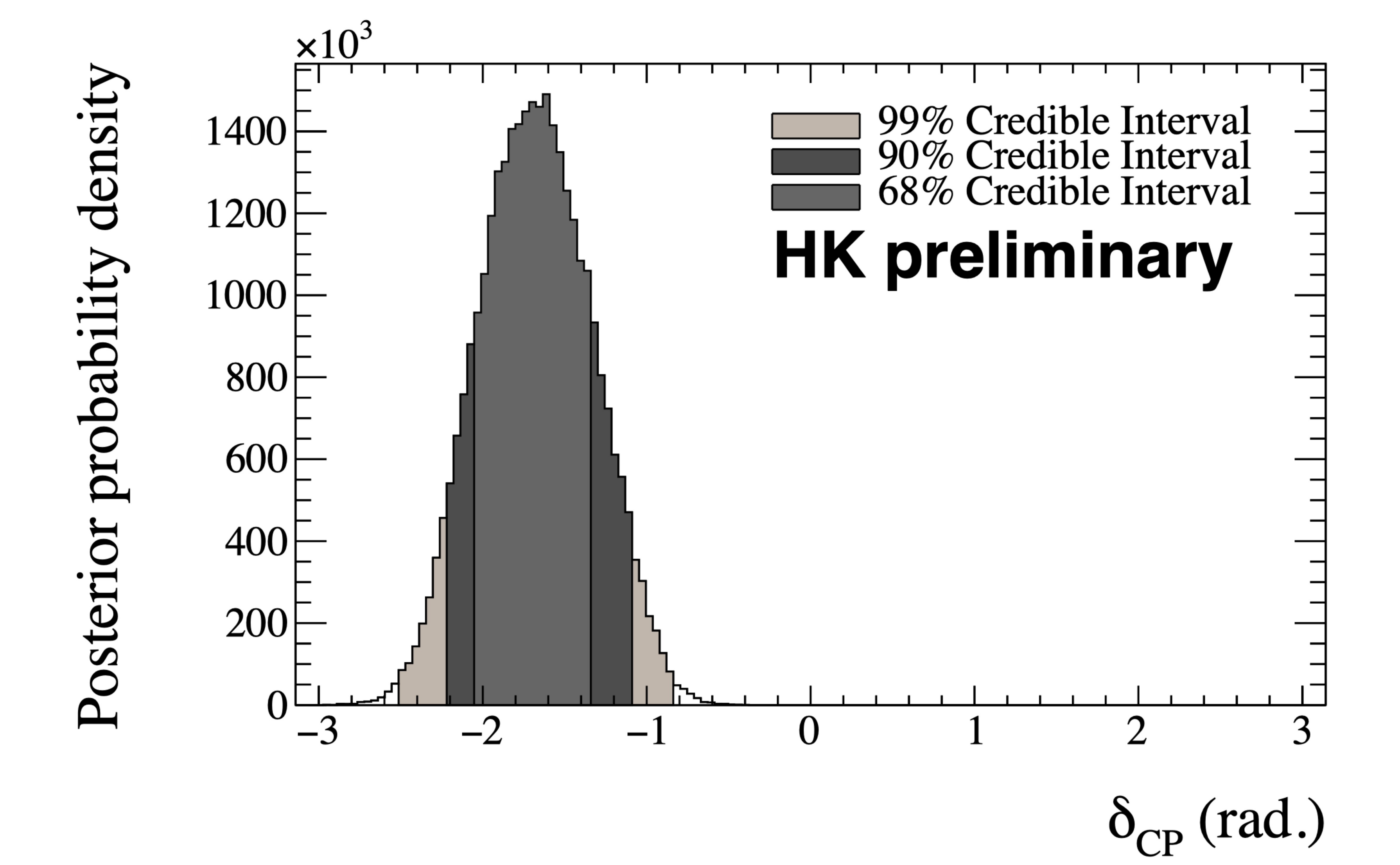

Fig 2: Posterior probabilities for δ_{cp} across both mass hierarchies with nominal value $\delta_{cp} = -\pi/2$

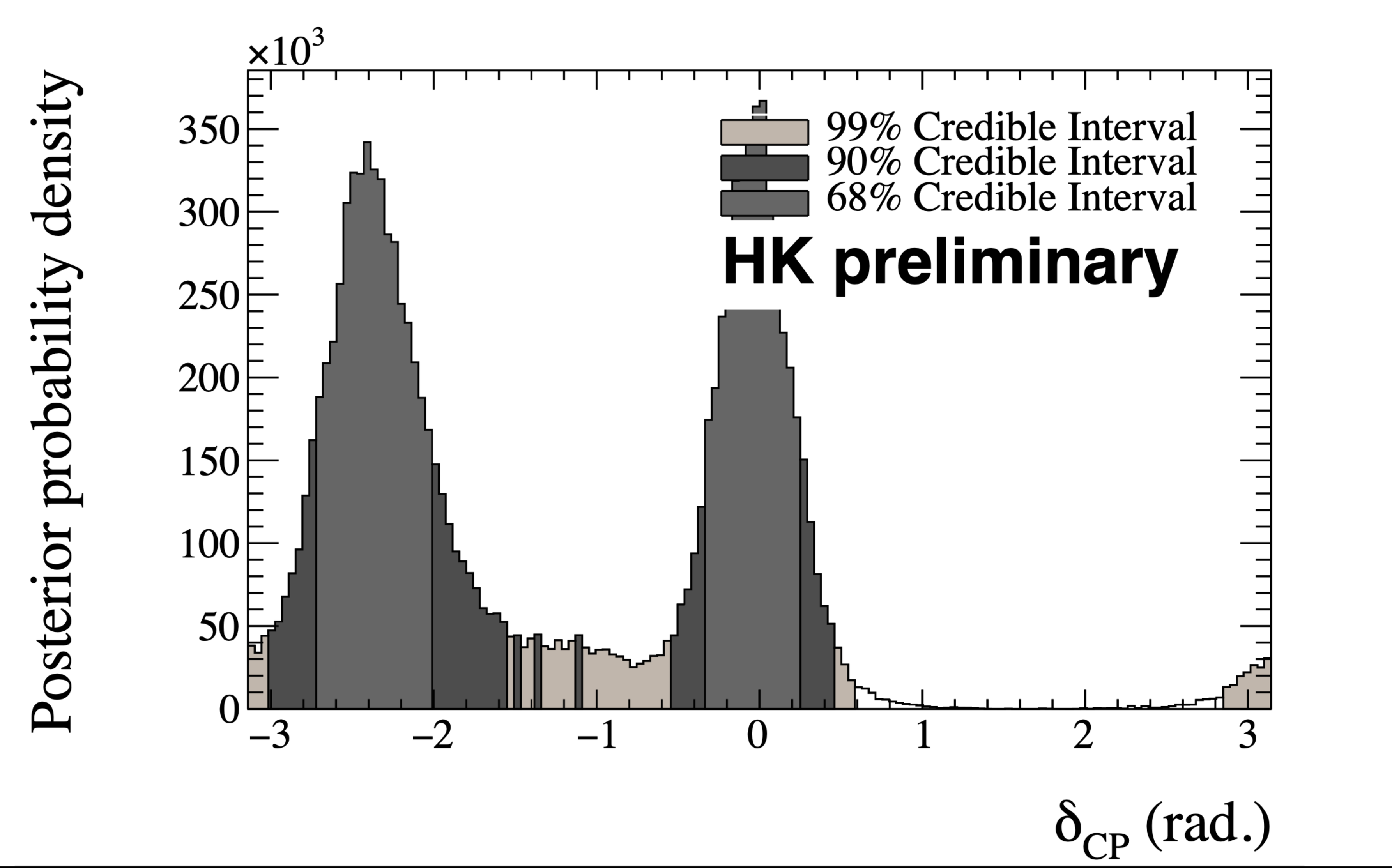

Fig 3: Posterior probabilities for δ_{cp} across both mass hierarchies with nominal value $\delta_{cp} = 0$

MaCh3 and T2HK

- MaCh3 currently runs mock T2HK fits by scaling up the 2018 and 2020 T2K models to Hyper-K statistics and applying Hyper-K flux tuning [Fig. 2,3].
- In figure 2, the IH is significantly supressed whereas figure 3 is bimodal with roughly equal preference for both mass hierarchies.
- The left peak of in figure 3 corresponds to an expected value of $\sim -3\pi/4$. This a result of baseline dependent matter effects.
- Effective comparisons with other fitters can only be made using 2018 code.
- There are substantial differences between MaCh3 and VALOR (a frequentist fitter), these are under investigation.
- Currently all fits have only varied values of δ_{cp}, but future fits are planned to examine other oscillation parameters.