Improving Hyper-Kamiokande sensitivity to CP violation with high precision near detector electron neutrino cross-section measurements

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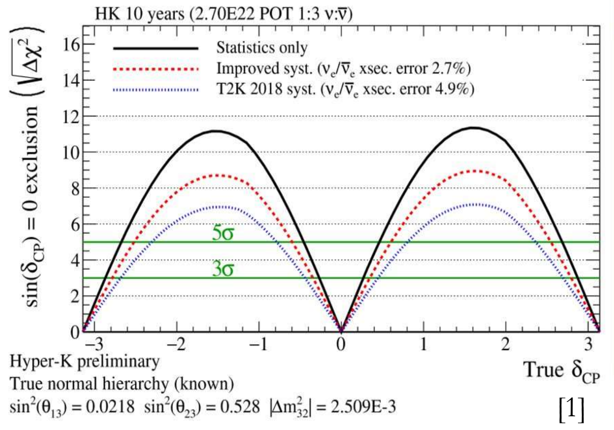
1. Hyper-K & the IWCD

- IWCD is a **new** near detector proposed for the long-baseline program of Hyper-K.
- **300t** water Cherenkov detector, **≈1km** from the beam production point.
- Moveable – able to measure different fluxes at different angles from the neutrino beam.
- Powerful ν_e cross-section measurement device.

Why ν_e ?

- Hyper-K CP violation sensitivity will be limited by ν_e and $\bar{\nu}_e$ cross-section uncertainty.
- Current uncertainty is **theoretically** driven and has limited scope to improve.
- Plan to move to experimental measurements.
- Current measurements are statistically limited.



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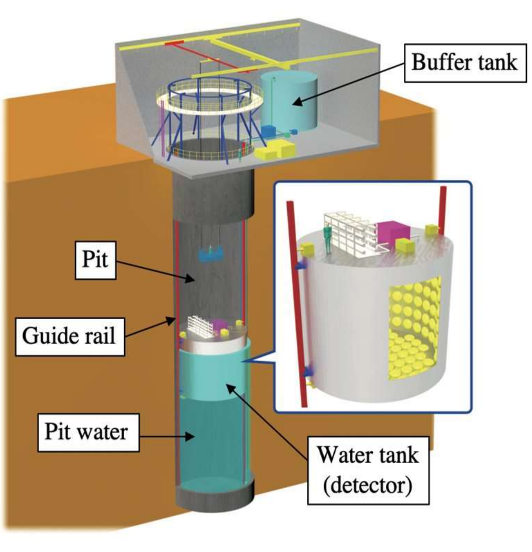
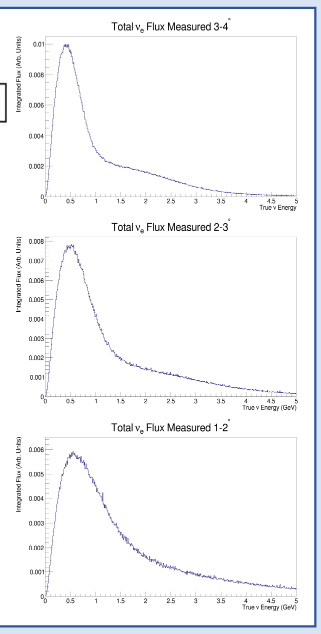




2. Near Detector Fit

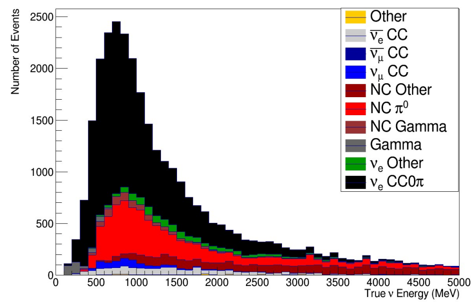
- For oscillation Physics measurements we need to **constrain a cross-section model** for neutrino interactions.
- Use data from a near detector, measuring flux **before** neutrino oscillations.
- Take each sample, bin in reconstructed variables and re-weight MC to find best fit point using **binned log-likelihood**.

$$-2ln(L) = \sum_{samples}\sum_{bins} 2\left(N_{pred} - N_{obs} + N_{obs} ln\left(\frac{N_{obs}}{N_{pred}}\right)\right) + \sum_{i}^{pars}\sum_{j}^{pars}(p_i - p_i^{prior})(V_{cov}^{-1})_{ij}(p_j - p_j^{prior})$$

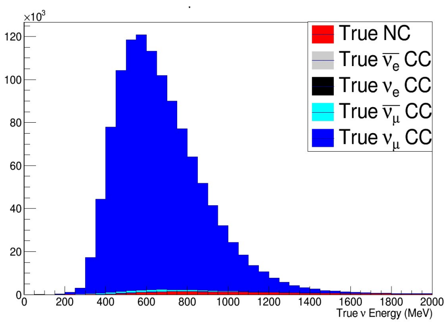
- Add prior constraint directly into the likelihood.
- Use a modified **T2K cross-section model**, in the future, Hyper-K will use a model with additional freedom.

3. Samples

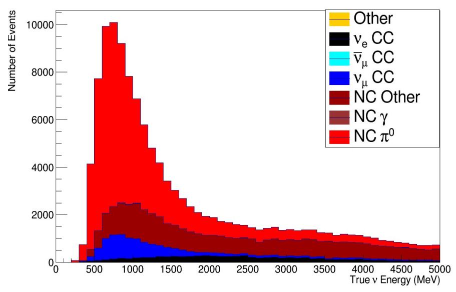
- **Three** IWCD ν-mode samples are used:



1 ring e-like events



1 ring μ-like events

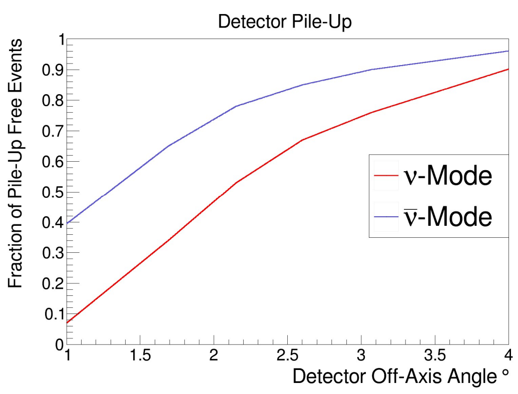


Neutral current-like events

- As well as these **three** in $\bar{\nu}$-mode.
- The μ-like sample will tightly constrain the cross-section model.
- The electron sample has over **18 000** CC electron neutrino events.
- Neutral current interactions from **high energy** neutrinos can reconstruct as **low energy** electrons.

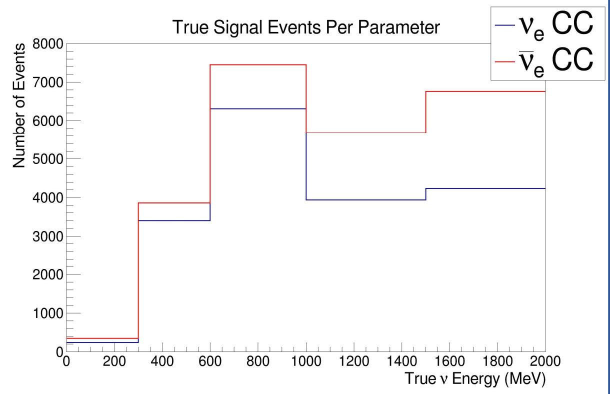
4. Pile-up

- IWCD is large enough that **multiple** neutrino interactions per **beam bunch** are likely.
- Many of these events are **difficult** to reconstruct correctly.
- More on-axis has higher event rate, higher pile-up and a **reduction** in useable events.
- Include systematic parameters for each detector position to account for pileup uncertainty.



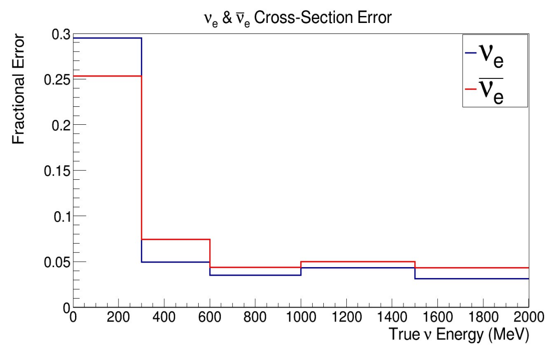
5. ν_e Cross-section Parameterisation

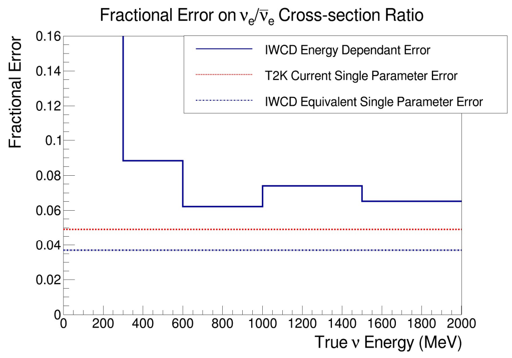
- We expect ν_e and ν_μ to be described by the same cross-section model.
- Due to complexity of nuclear interactions, it is not clear that this is the case.
- Grant **additional freedom** to ν_e and $\bar{\nu}_e$ to vary their cross-sections **relative** to ν_μ and $\bar{\nu}_\mu$.
- Include different, free parameters for each energy range.
- Below **2%** statistical error for parameters of interest around 600 MeV.



6. Results

- Cross-section constraint as a function of **incident neutrino energy**.
- 7×10^{21} Protons on target in ν-mode, 21×10^{21} in $\bar{\nu}$-mode.
- Poor constraint in the low statistics, background dominated region.

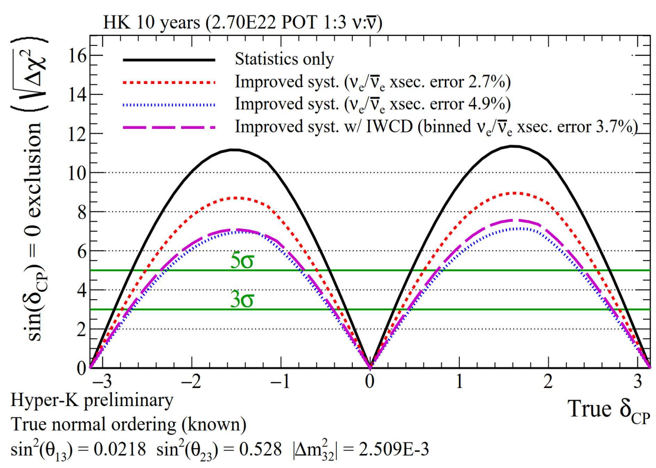




- Due to strong **anticorrelation** between the parameters, integrating this cross-section over the Hyper-K far detector event distribution yields an equivalent error of **3.7%** on the relative appearance rate of ν_e to $\bar{\nu}_e$.
- Improvement over the **4.9%** theoretical error used by T2K.

7. Impact

- Including this energy dependent constraint in a Hyper-K oscillation fitter.
- Improvement in overall CP sensitivity relative to theoretical cross-section uncertainty.
- **5σ** rejection of CP conservation for more than **50%** of true values of δ_{CP}.



References

[1] Hyper-K Technical Design Report

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