Hyper-Kamiokande LBL Physics Sensitivity

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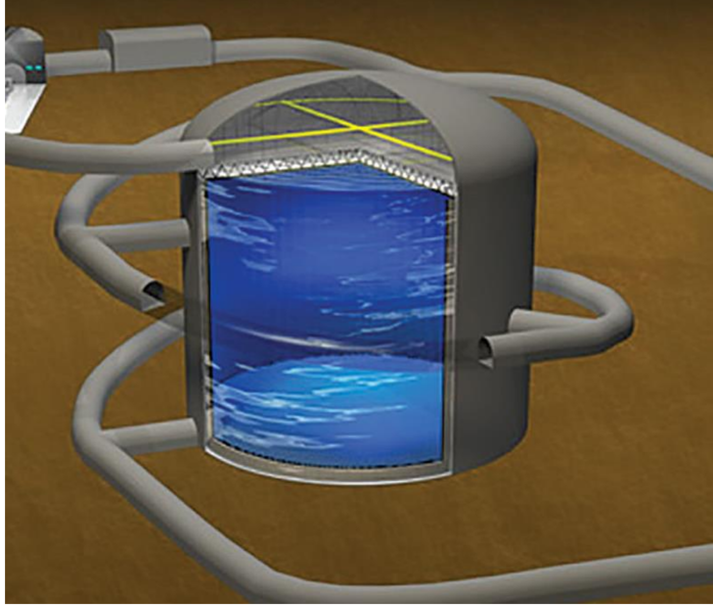
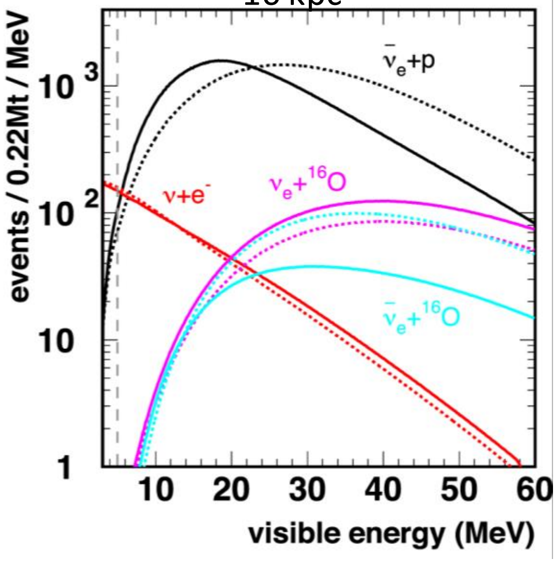
On behalf of the Hyper-Kamiokande collaboration

Hyper-K

- Builds on the success of Super-Kamiokande
- Water Cherenkov detector, 186 kton fiducial
- 20 000 inner detector 50 cm PMTs
- Rich physics program
  - Proton decay
  - Atmospheric neutrinos
  - Supernova + relic supernova
  - Solar neutrinos
  - **Beam LBL neutrino oscillation**

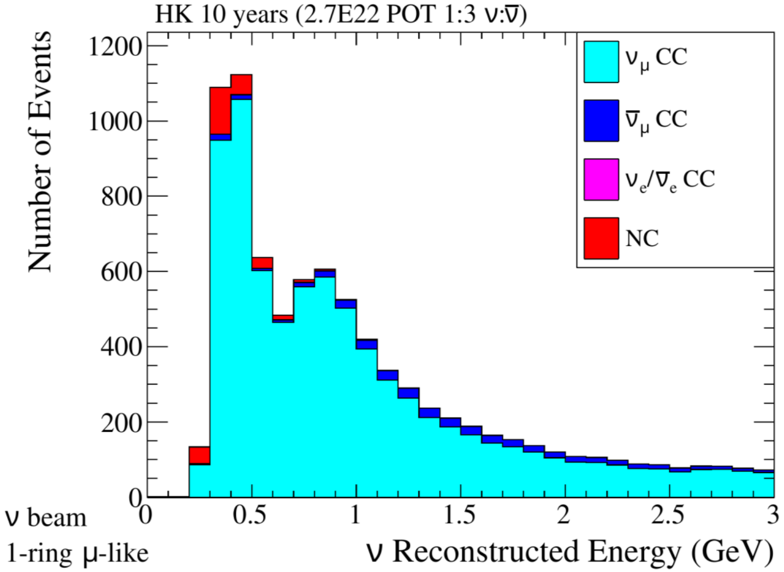


HK Supernova neutrino appearance spectrum 10 kpc

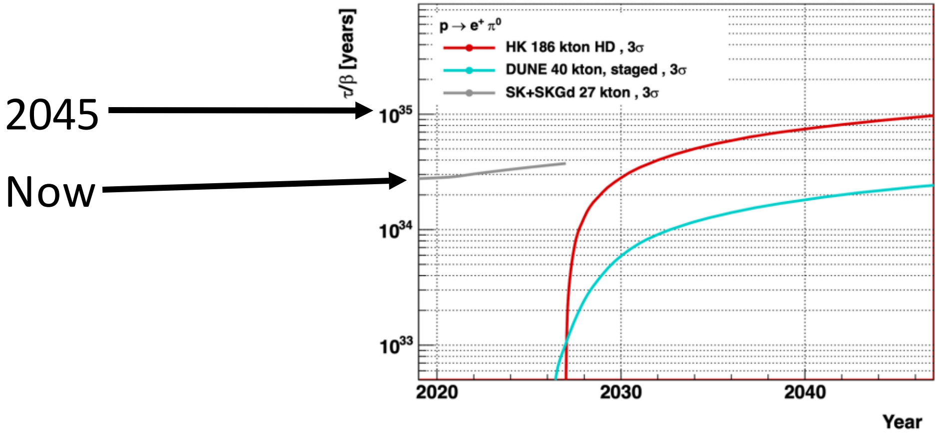


doi:10.3847/1538-4357/abf7c4

HK LBL ν_μ spectrum



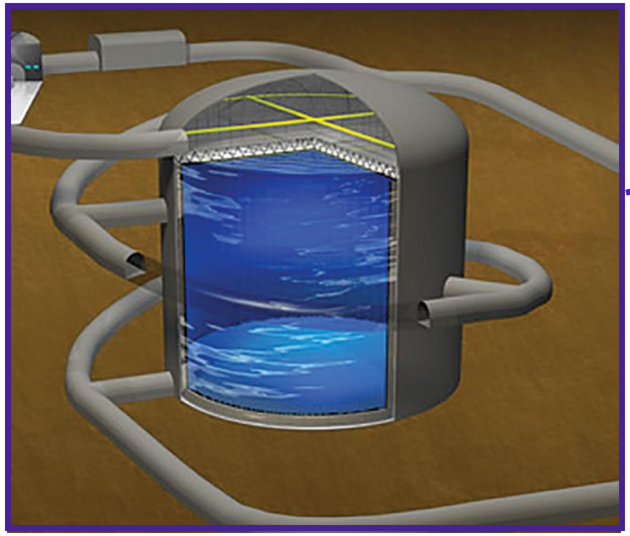
HK p->e^+ π^0 decay sensitivity

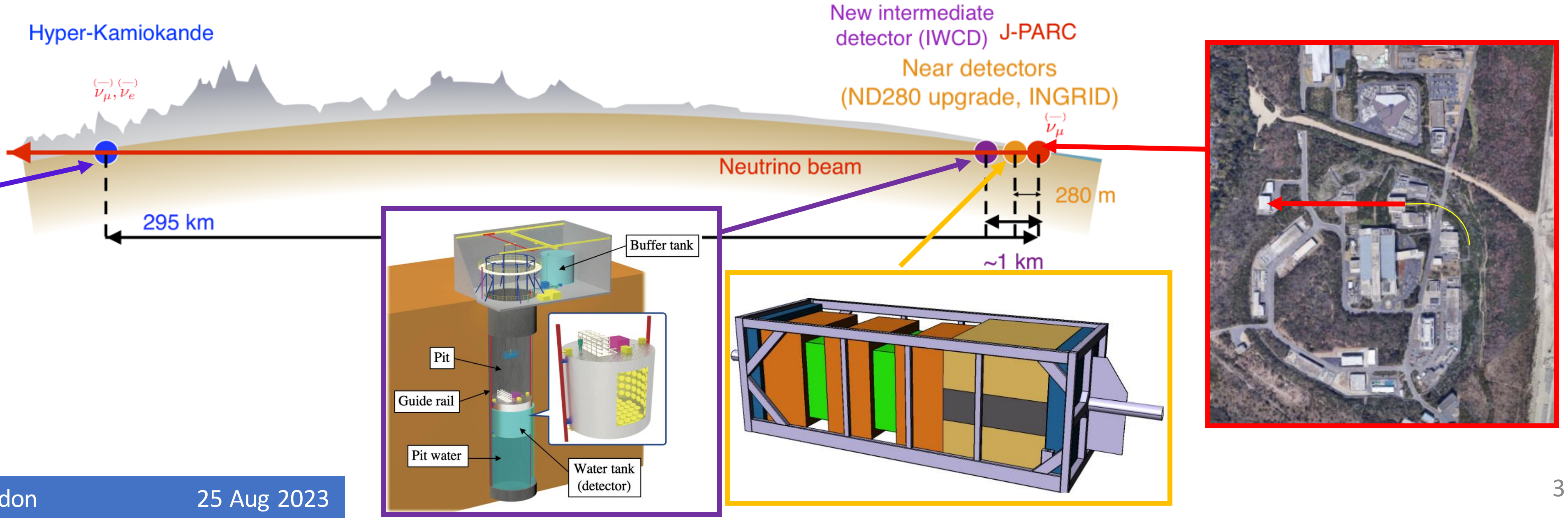


(See talk by N. McCauley for more)

Hyper-K LBL Program

- Builds on success of T2K
- Produce a high-power, selectable ν_μ or $\bar{\nu}_\mu$ dominated neutrino beam at J-PARC
- Measure neutrino flux and cross section with detectors close to beam source, before oscillation
- Observe neutrinos 295km from source in Hyper-K, after they have oscillated
  - Two observable channels: $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$
  - Use knowledge of flux and interactions from near detectors to extract oscillation information



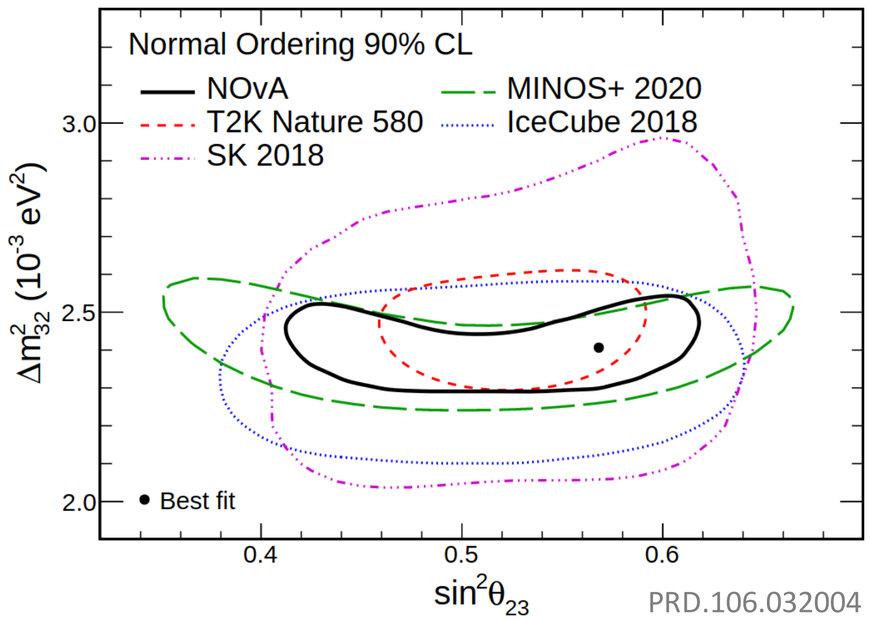


Hyper-K LBL Physics Goals

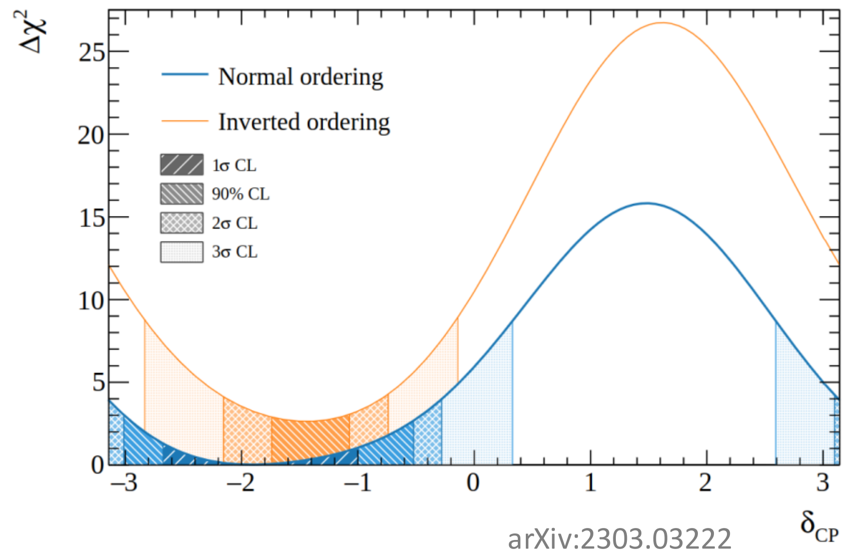
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Does $\sin^2\theta_{23} = 0.5$?
  - If not, which octant is it?
- Precision measurement of Δm^2_{32}
- Independent cross-check on reactor θ_{13} measurements
- Mass ordering with LBL + atmospheric
- Do neutrinos violate CP symmetry?
  - If so, what is the value of δ_{CP}
  - Key information for baryon asymmetry

Global beam & atmospheric results

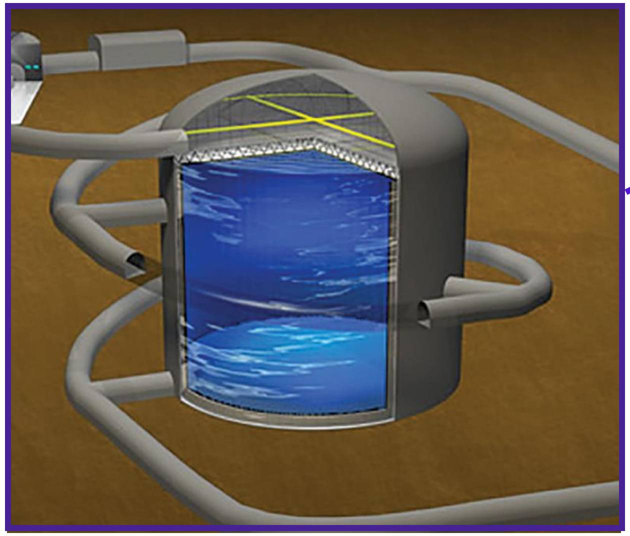


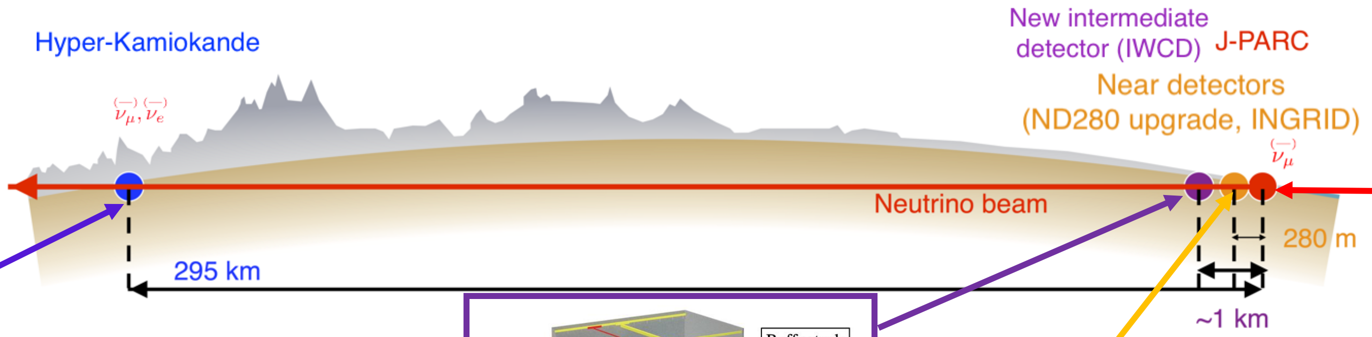
T2K δ_{CP} result

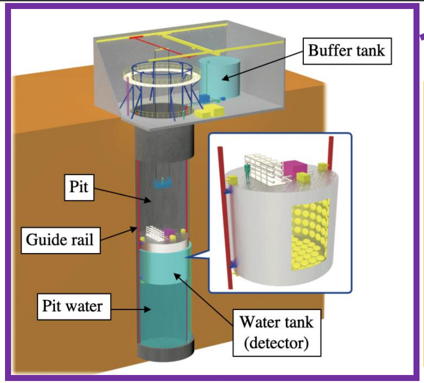


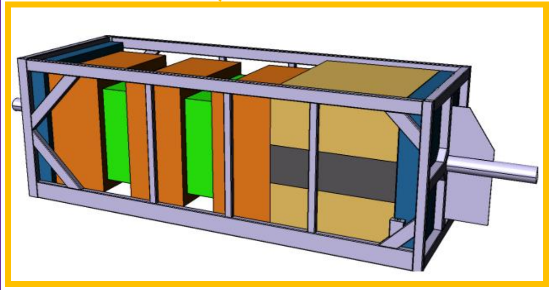
The Hyper-K LBL Experiment

- To achieve these LBL physics goals, Hyper-K needs:
  - Huge increase in statistics over existing LBL experiments:
    - 186 kton fiducial mass, >8 times that of Super-K
    - 1.3 MW ν_μ or $\bar{\nu}_\mu$ dominated neutrino beam, more than double T2K beam power
    - Combined, over 10 years of running, 1:3 $\nu:\bar{\nu}$ mode, expect ≈×40 current T2K far-detector statistics
  - Improvement in understanding of neutrino flux, cross section and detector effects:
    - Suite of new and upgraded near detectors
    - Bottom-up approach to detector systematics



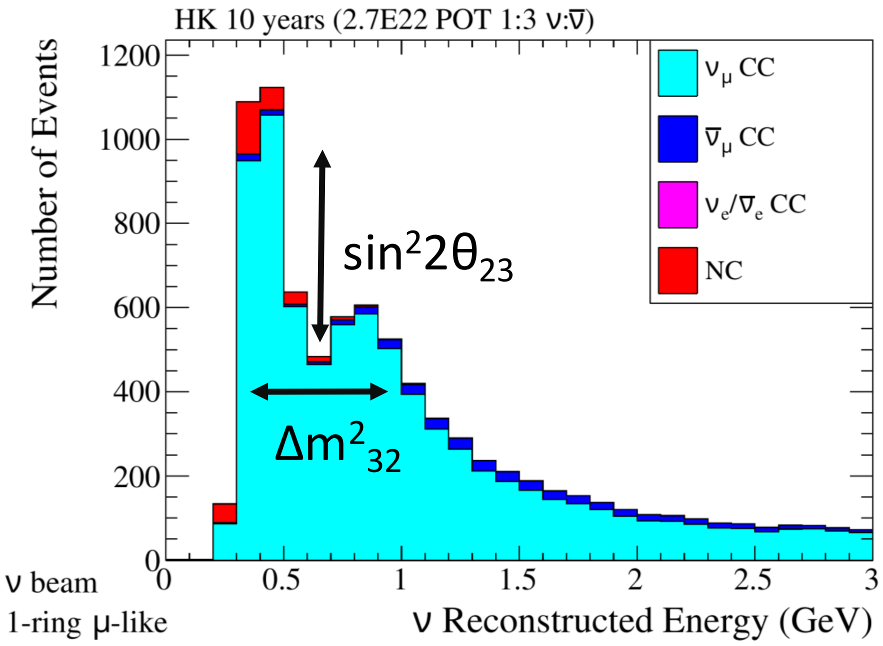






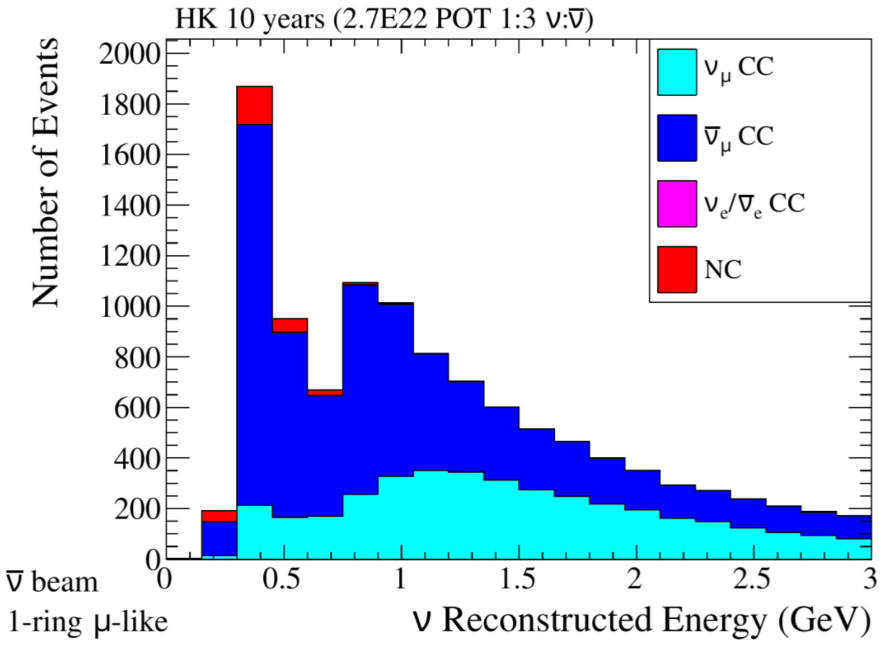
ν_μ disappearance

- The majority of events seen at HK will be $\nu_\mu \rightarrow \nu_\mu$
- Position and strength of oscillation dip gives Δm^2_{32} and $\sin^2 2\theta_{23}$



	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	**NC**	**Total**
ν-mode ν_μ CCQE-like	8584	480	0.24	0.01	2.32	0.01	283	9349
ν̄-mode ν_μ CCQE-like	4399	7688	0.28	0.24	0.33	0.42	286	12375

ν_μ-like events, 10 years, $\sin^2\theta_{23}=0.58$, $\Delta m^2_{32}=2.509\times10^{-3}\text{eV}^2$, normal ordering



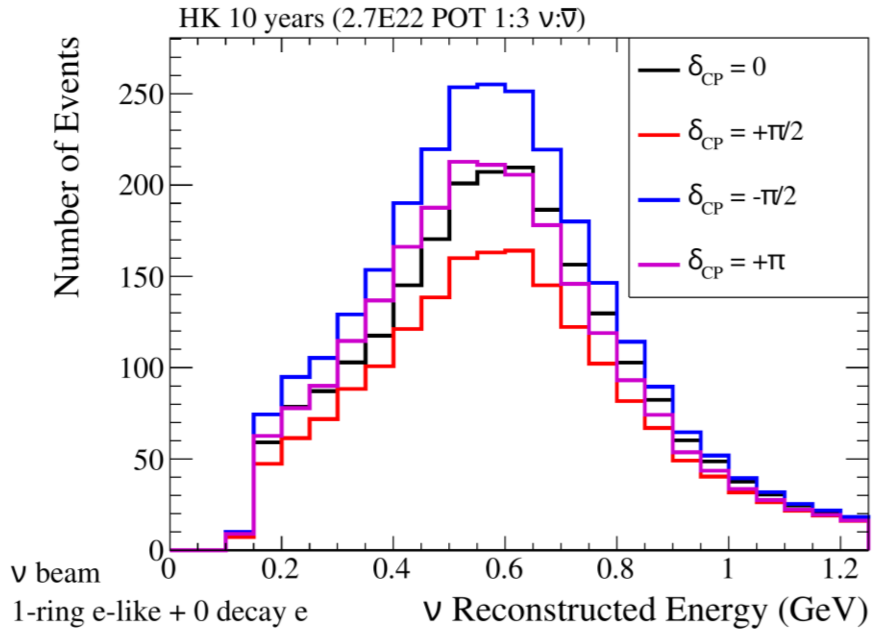
ν_e appearance

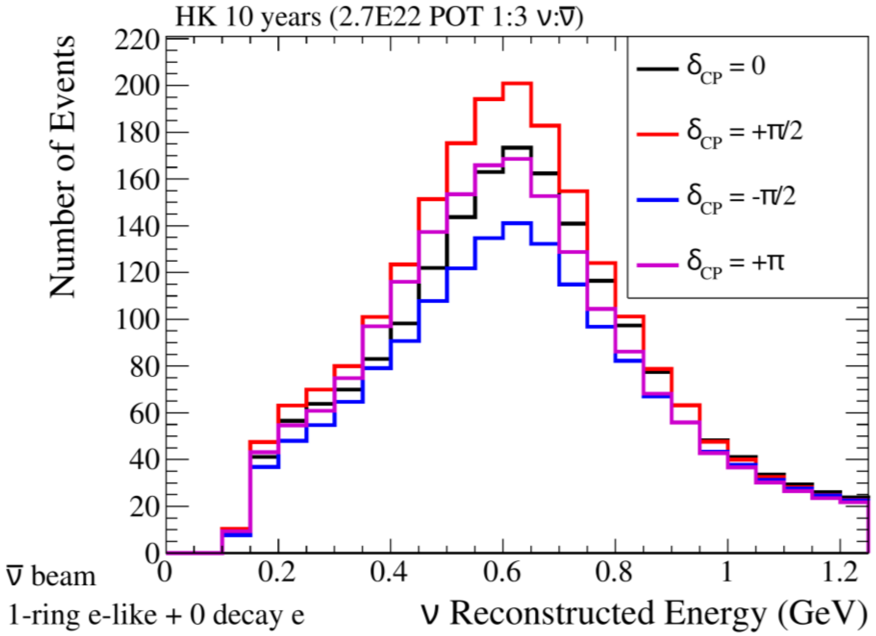
- Sensitivity to δ_{CP} and octant of θ_{23} comes primarily from $\nu_\mu \rightarrow \nu_e$ oscillations

- δ_{CP} changes ν_e and $\bar{\nu}_e$ oscillation probability in opposite directions

	δ_{CP} = -π/2	δ_{CP} = 0	δ_{CP} = +π/2	δ_{CP} = +π
ν-mode ν_e CCQE-like	2740	2285	1846	2301
ν-mode ν_e CC1π-like	258	223	179	214
$\bar{\nu}$-mode ν_e CCQE-like	1624	1883	2118	1859

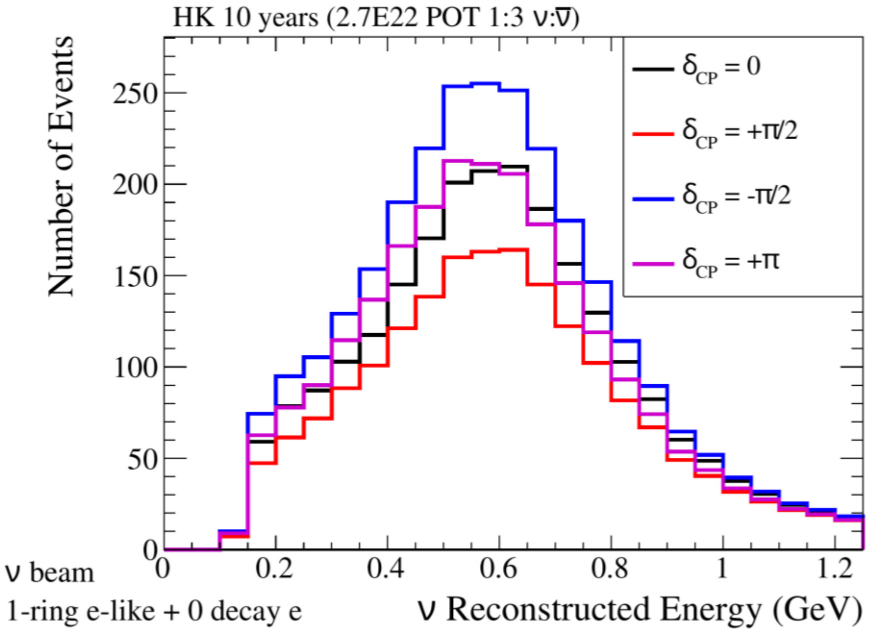
ν_e-like events, 10 years, $\sin^2\theta_{23}$=0.58, Δm^2_{32}=2.509x10^{-3}eV^2, normal ordering

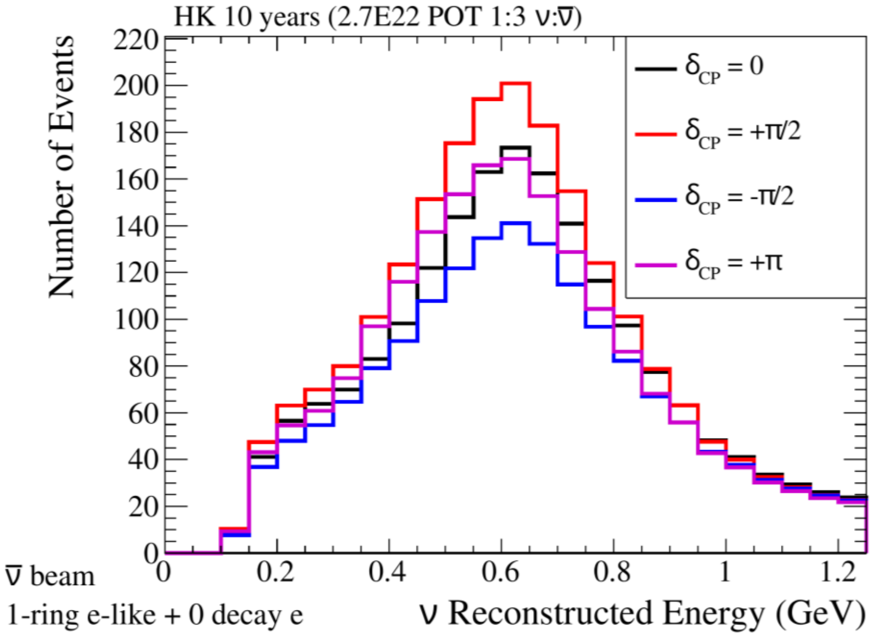




Aside: ν_e cross section

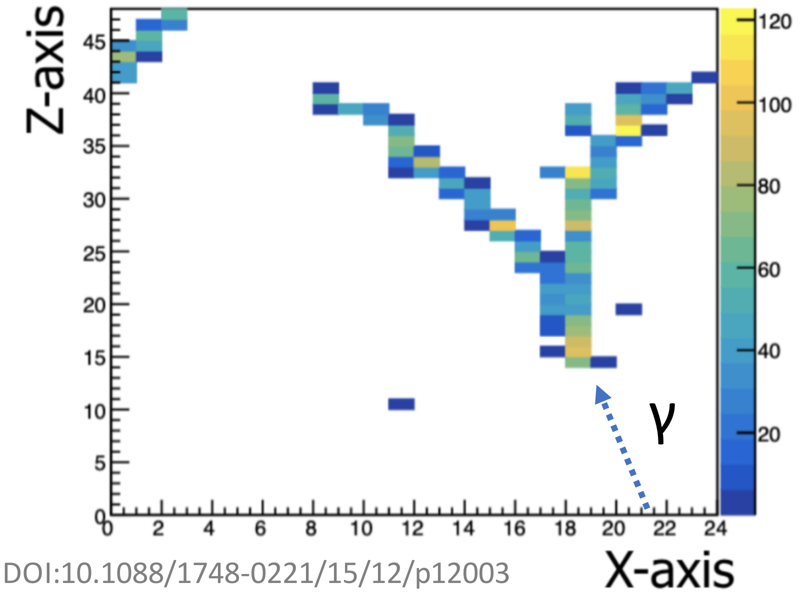
- HK's δ_{CP} sensitivity derives from $\nu_e/\bar{\nu}_e$ appearance rate
- $\nu_e/\bar{\nu}_e$ cross-section ratio can also affect this
- T2K currently uses a 4.9% prior uncertainty on this ratio with very little data constraint.
- This would limit δ_{CP} sensitivity, HK intends to measure this ratio as precisely as possible, with current studies focused on a 2.7% precision





ND280

- Magnetised plastic scintillator and TPC near detector
- Constrain neutrino flux, interaction cross section and wrong-sign component
- Currently undergoing upgrade with higher granularity super Fine Grained Detector (sFGD) and high angle TPCs. (See talks by L. Munteanu, D. Nguyen)
- Upgrade provides better e/γ separation and lower proton momentum threshold due to higher granularity of sFGD



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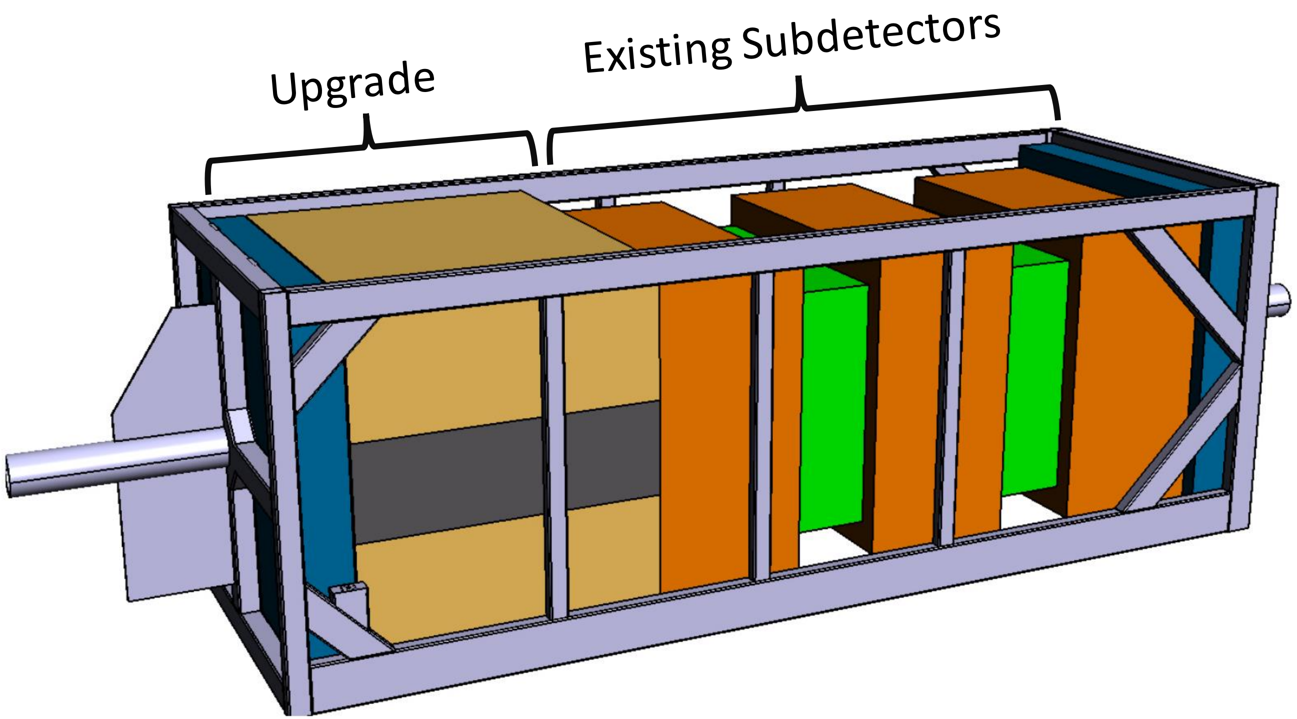
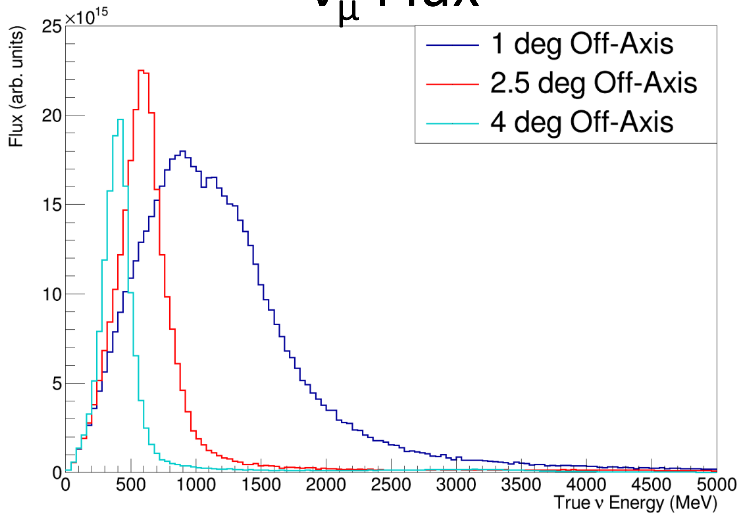
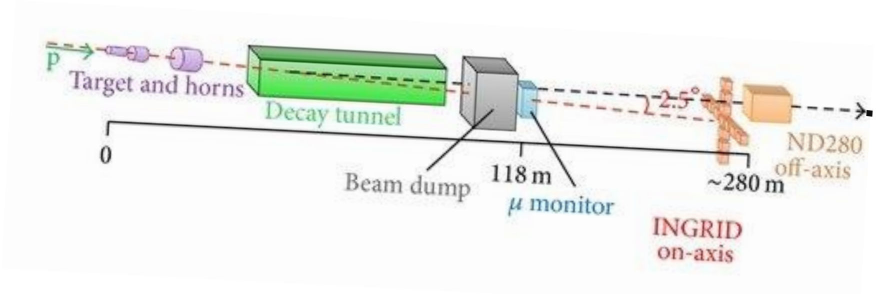


Intermediate Water Cherenkov Detector

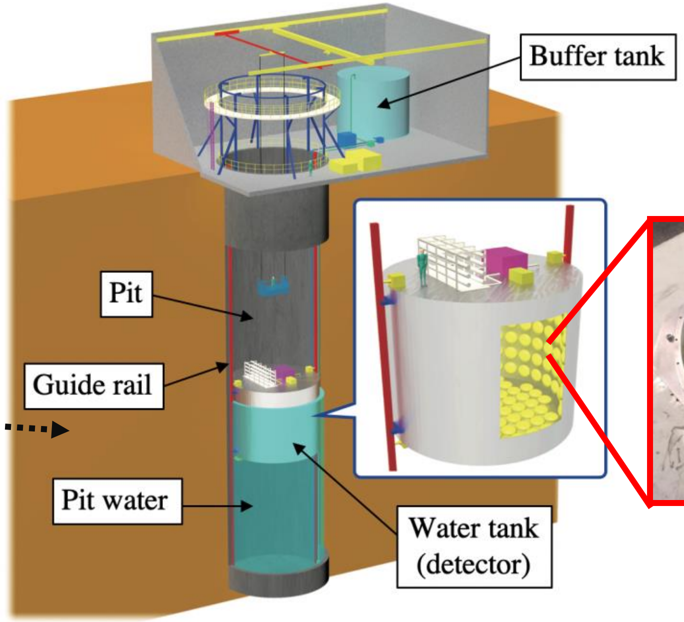
- 600 t water Cherenkov detector ~1km from the beam in a vertical shaft
- Pion/muon decay kinematics results in different neutrino fluxes along the shaft (see M. Wilking's talk)
- Small multi-PMTs provide high-granularity and time resolution in a relatively small detector
- Excellent e/μ PID, combined with large target mass, IWCD can select the 1% ν_e component of the beam

ν_μ Flux



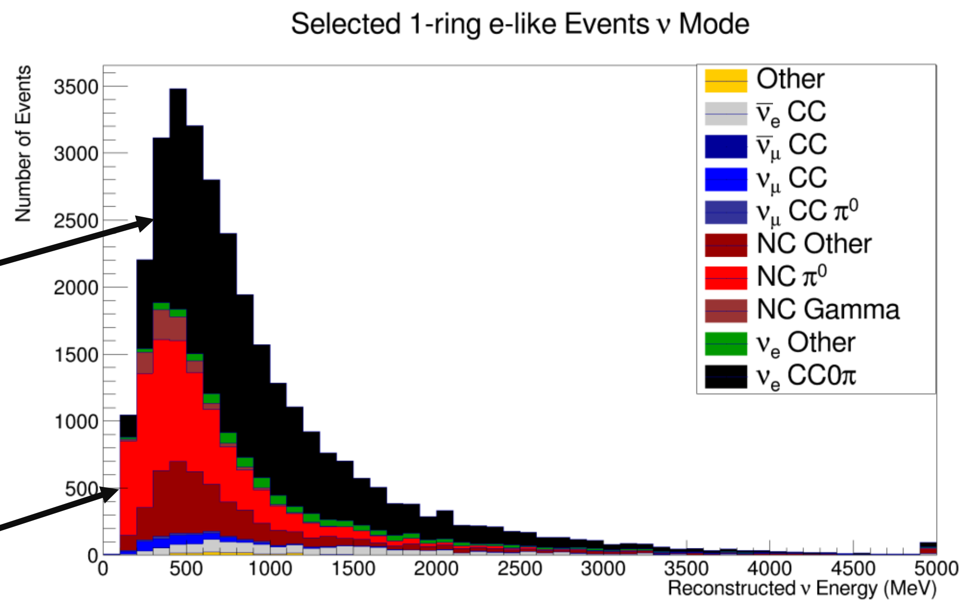


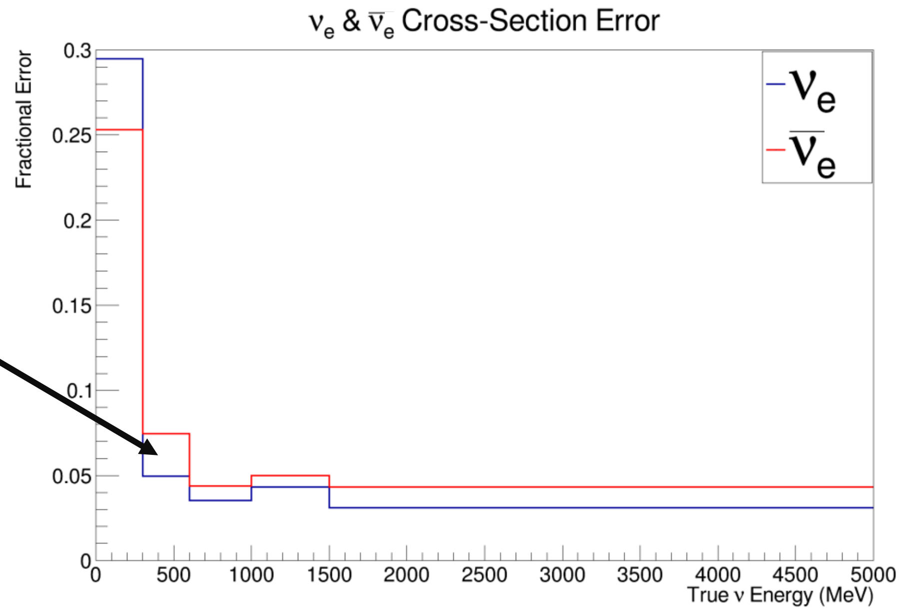
~1km



IWCD ν_e measurement

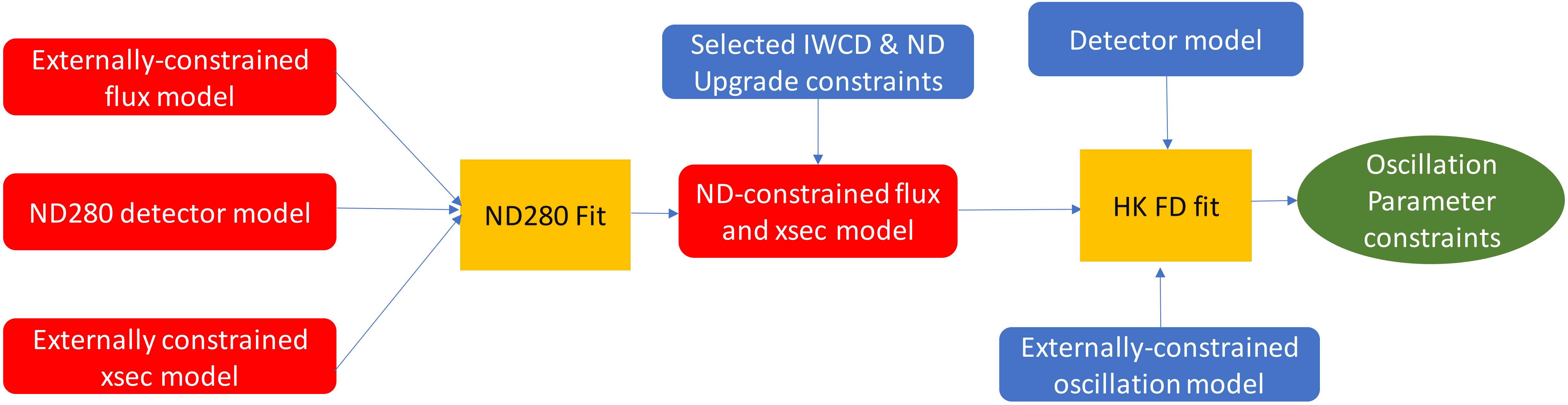
- Current IWCD fit uses six samples: ν_e, ν_μ and NCπ^0, each in ν and $\bar{\nu}$ mode
- Select over 18000 ν_e events in ν-mode
- ν_μ (>1M ν mode events) constrains CC cross section & flux, NCπ^0 constrains NC background to ν_e samples
- Integrating over HK ν_e appearance spectrum, obtain 2.94% uncertainty on $\nu_e/\bar{\nu}_e$ rate ratio with analysis improvements possible
- Total uncertainty is lower than on each individual parameter due to correlations
- Preliminary studies with ND280 upgrade + IWCD achieve better than 2.7% uncertainty, helped by ND280 charge selection





Analysis Procedure

- To obtain oscillation parameter constraints from these HK spectra, adopt an approach similar to T2K
- Use a near detector to constrain a model of flux and neutrino interaction cross-section
- Add selected constraints from the IWCD fit and ND upgrade studies
- Use this constrained systematic model in an oscillation fit to the far-detector data



Systematic modelling

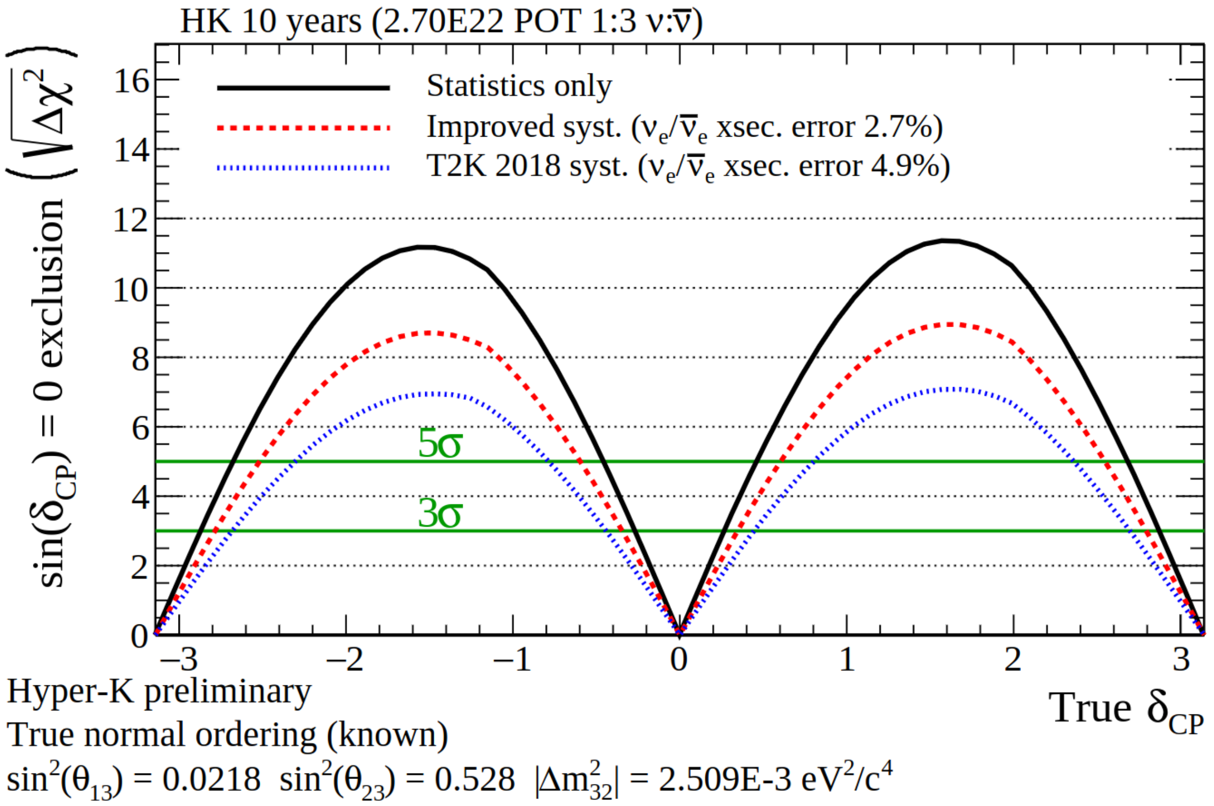
- Making use of T2K 2018 model for flux, cross section and detector systematics.
- Three scenarios investigated:
  - **Statistics only**, no flux, cross section or detector uncertainty
  - **T2K 2018 systematics,** T2K ND fit with 2018 statistics and 2018 SK detector uncertainties
  - **HK Improved systematics**, T2K 2018 ND fit systematics scaled by sqrt(N_{T2K}/N_{HK}), preserving correlations
    - A 1% minimum uncertainty is enforced on all parameters
    - Additional constraint from IWCD and ND280 upgrade on specific parameters
    - 2.7% error on $\nu_e/\bar{\nu}_e$ cross-section ratio

Physics Sensitivities

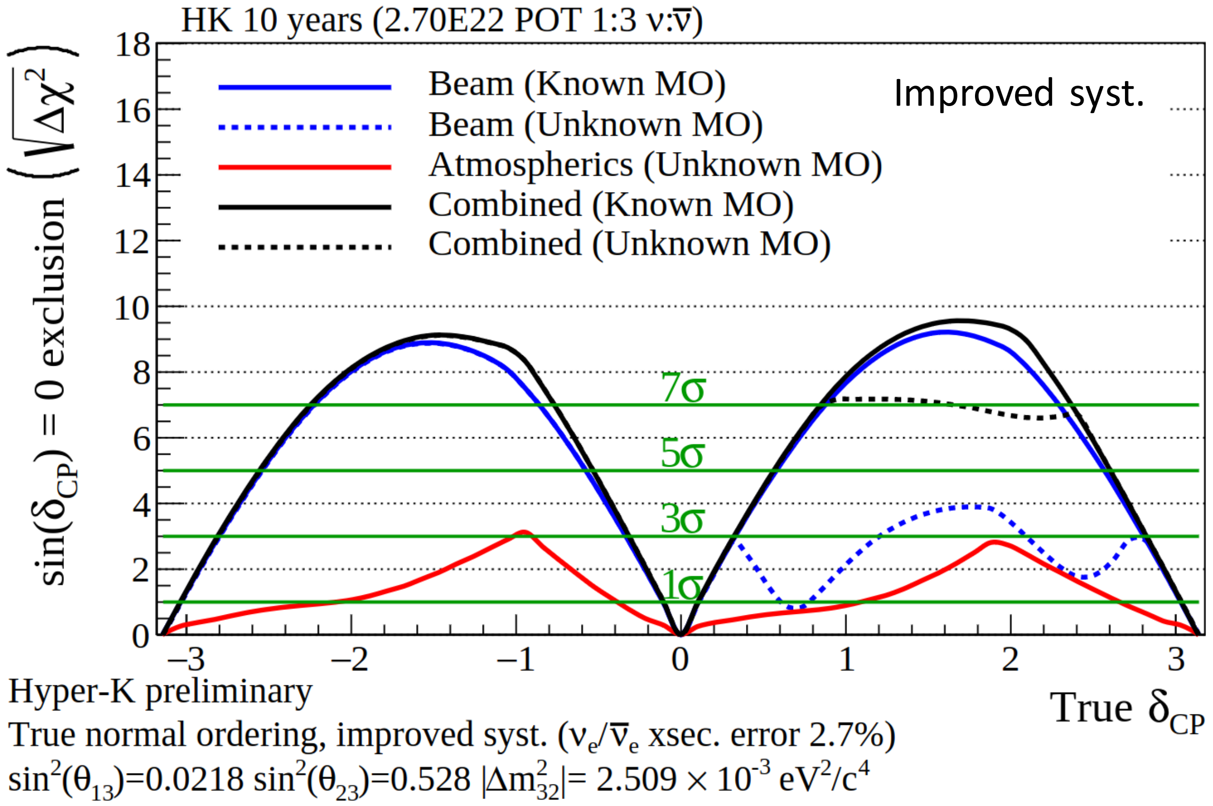
CP violation sensitivity

- Ability to exclude δ_{CP} = 0, ±π as a function of true δ_{CP}
- Systematic uncertainties play a key role in sensitivity
- Beam + atmospherics improves sensitivity over beam alone when MO is unknown

Beam only, known MO

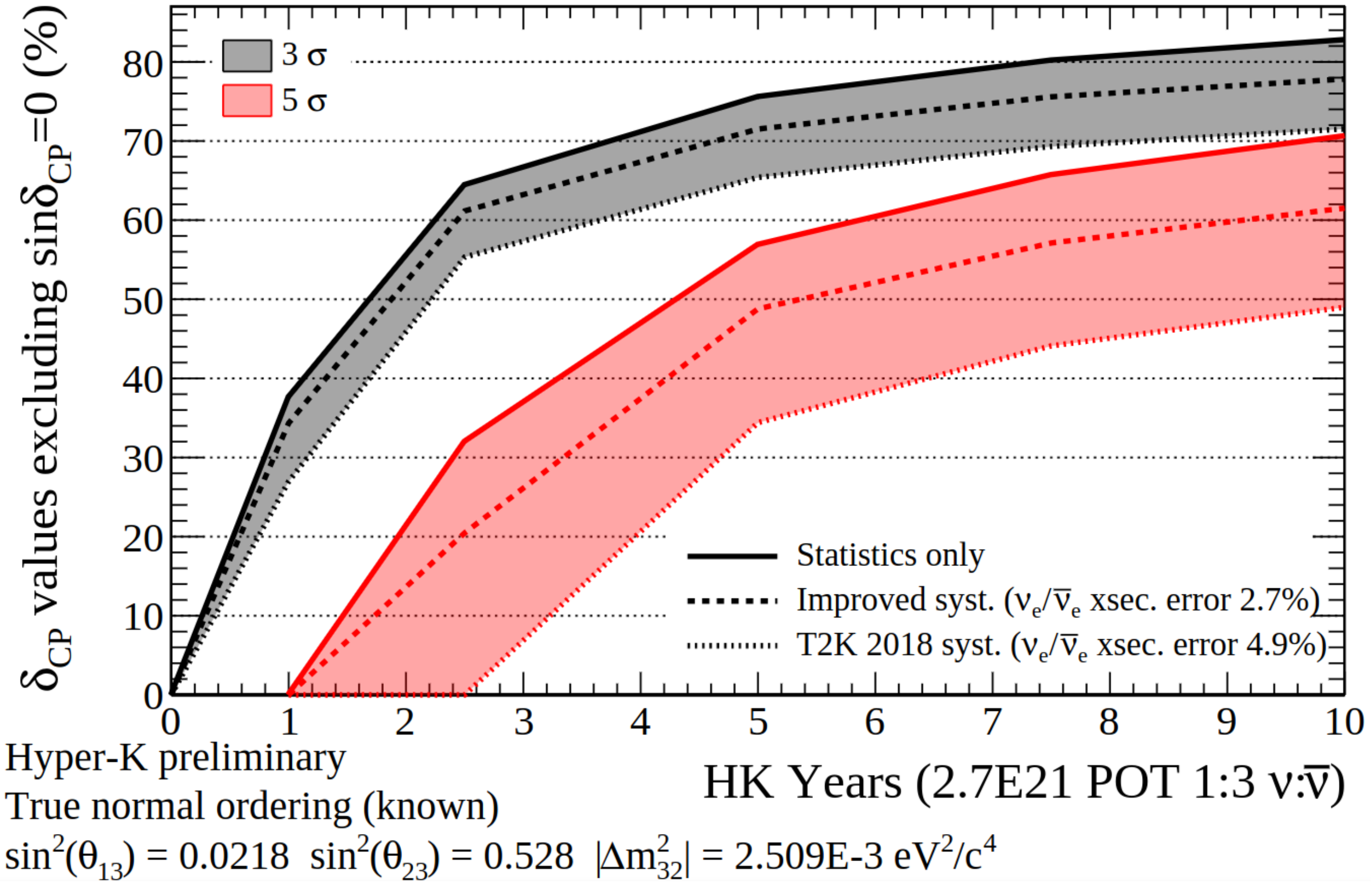


Beam + atmospherics, unknown MO



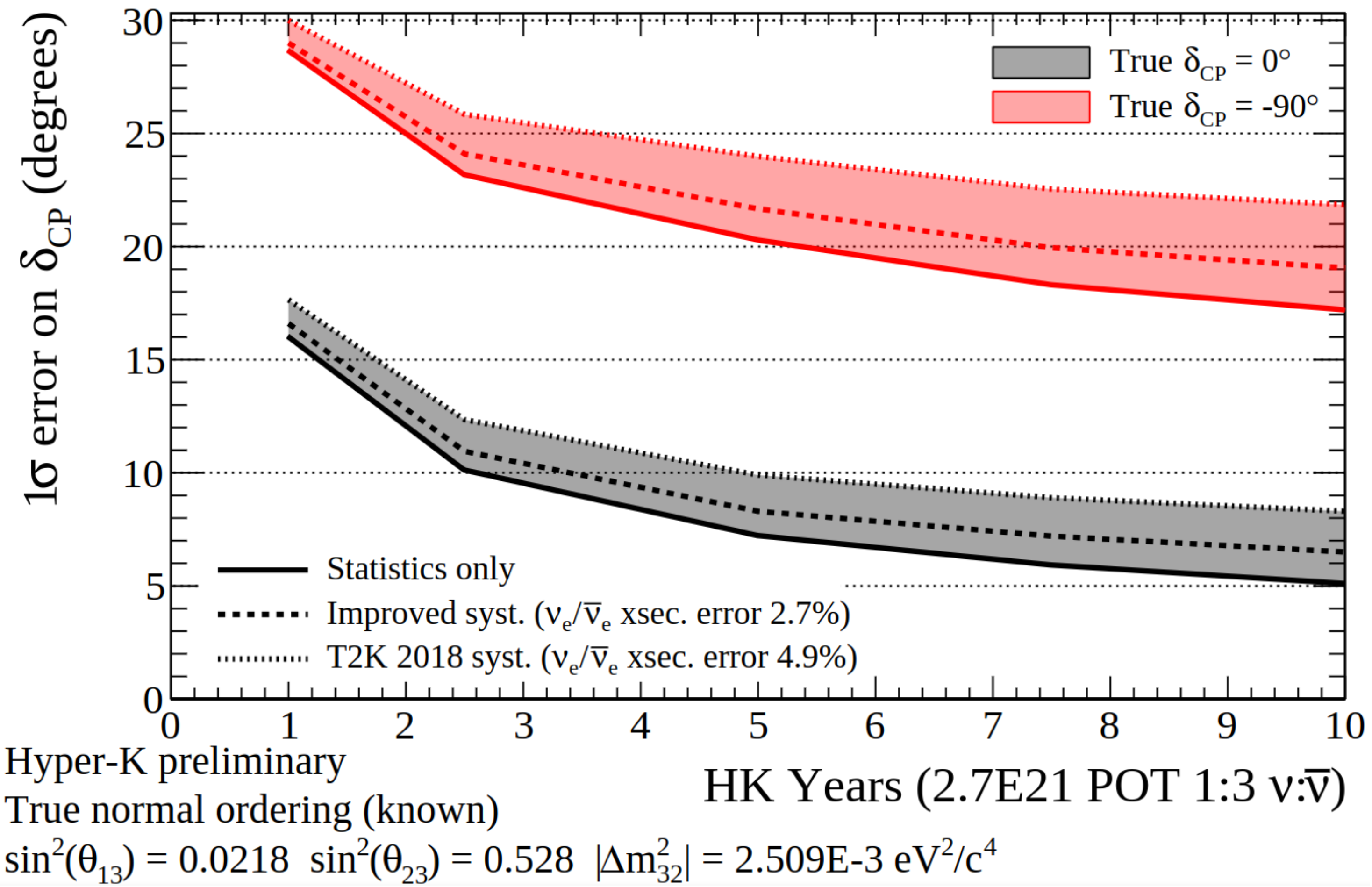
CP violation sensitivity

- Fraction of δ_{CP} values excluding CP conservation as a function of exposure
- Exclude CP conservation to 5σ for >60% of true δ_{CP} values, >75% to 3σ



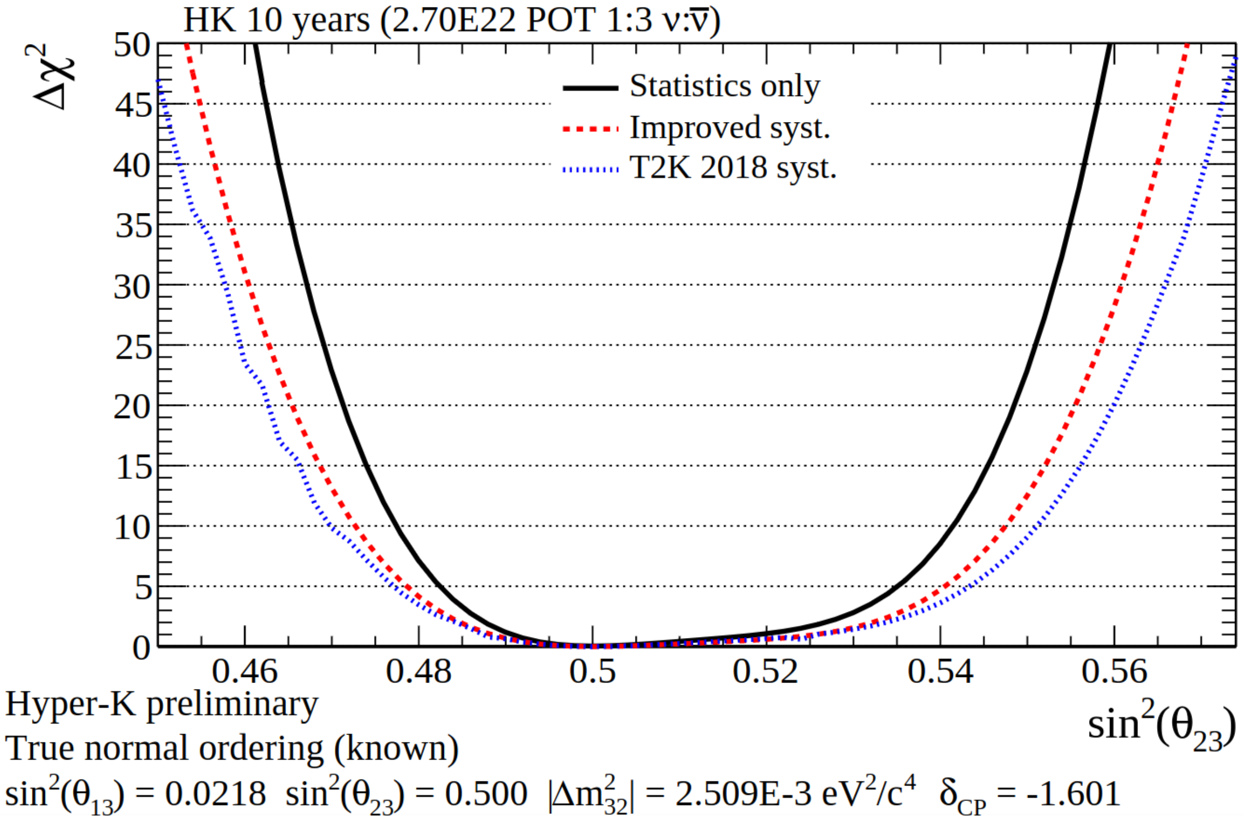
δ_{CP} Resolution

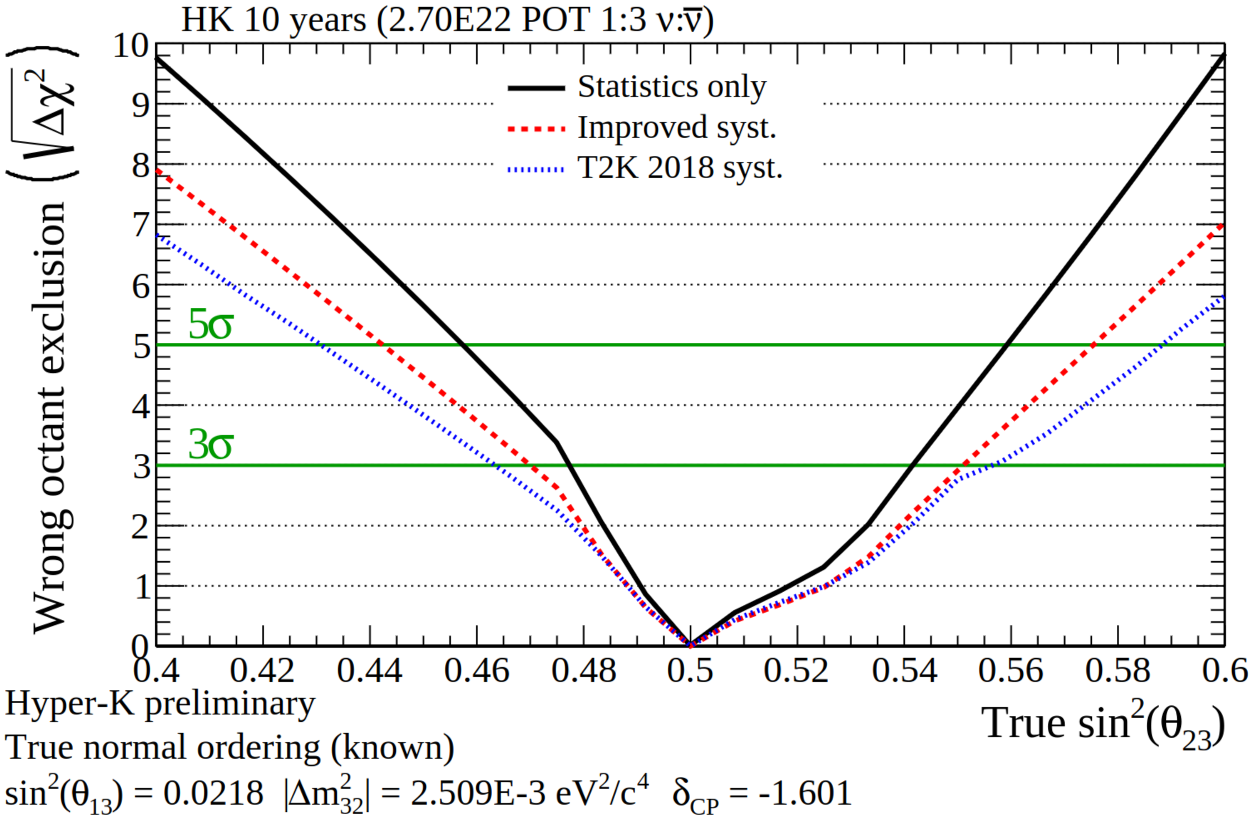
- 1σ precision on the measurement of δ_{CP}
- Ranges between 6 and 20 degrees
- Lowest precision around maximal CP violation where ν_e event rate changes most slowly
- $\nu_e/\bar{\nu}_e$ cross-section is leading systematic and most significant close to CP conserving values



θ_{23} Precision & Octant

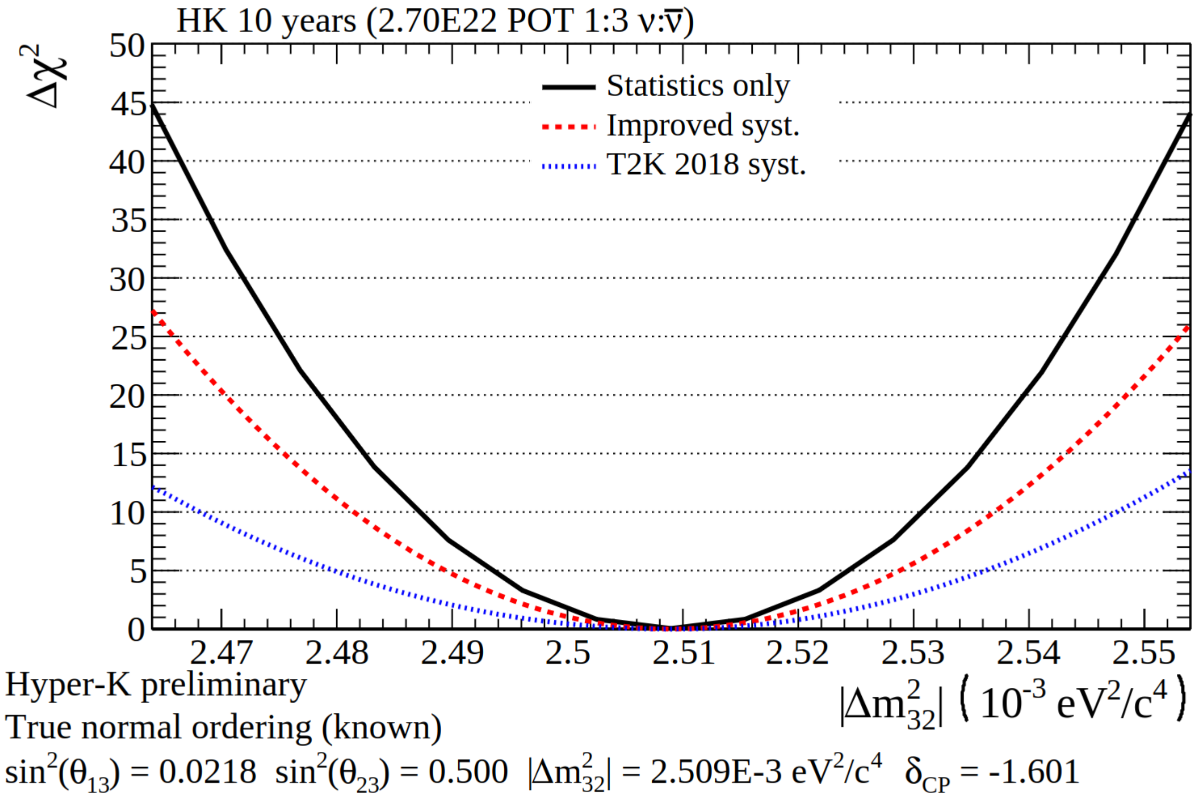
- Measurement precision depends strongly on true θ_{23} value
- Beam only, improved systematics can exclude wrong-octant to 3σ for true $\sin^2\theta_{23} < 0.47$ or $\sin^2\theta_{23} > 0.55$

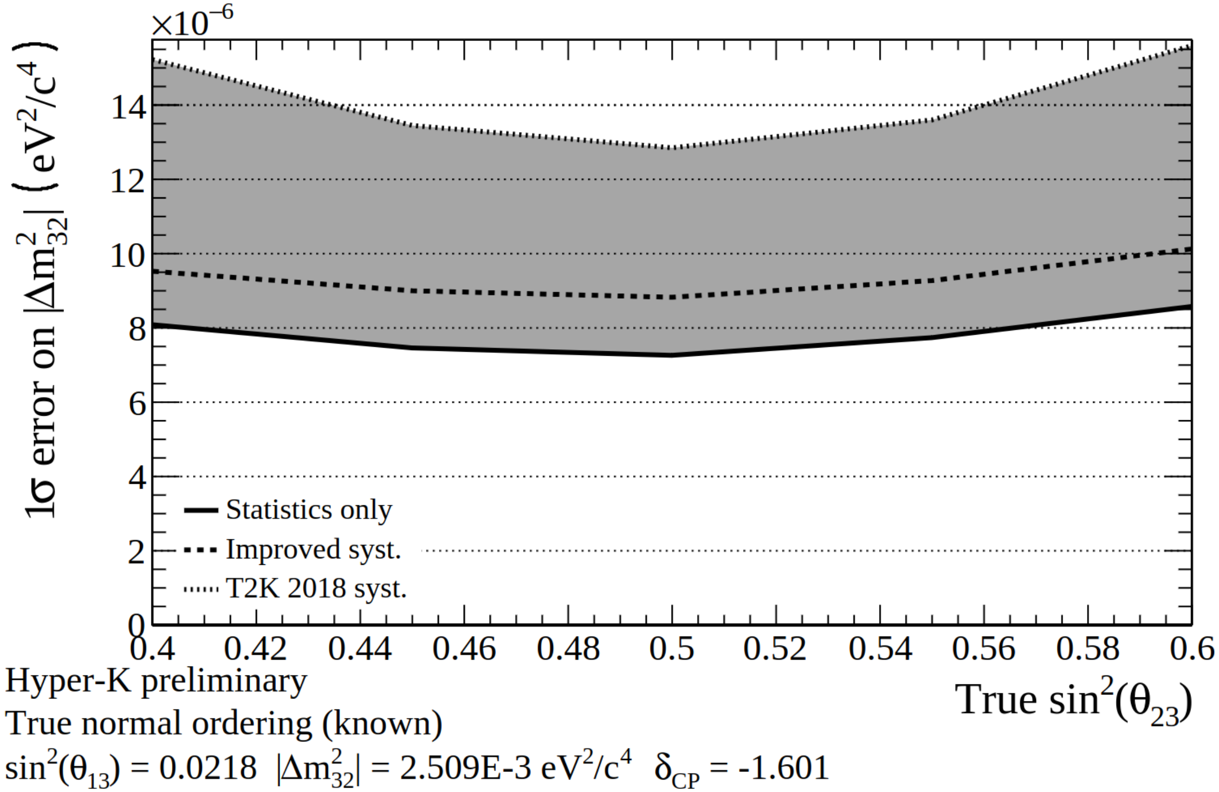




Δm^2_{32}

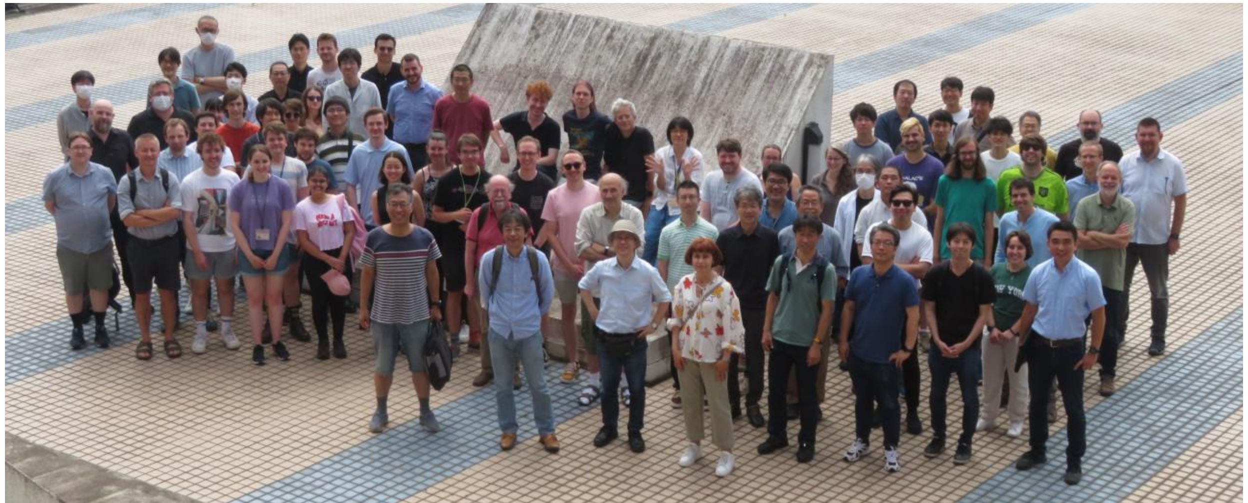
- 1σ precision on Δm^2_{32} has a small dependence on θ_{23} value
- 1σ precision measurement 9×10^{-6} eV^2 possible, cf. 50×10^{-6} eV^2 from T2K (arXiv:2303.03222)
- Improved systematic model increases precision by 30% over existing systematics





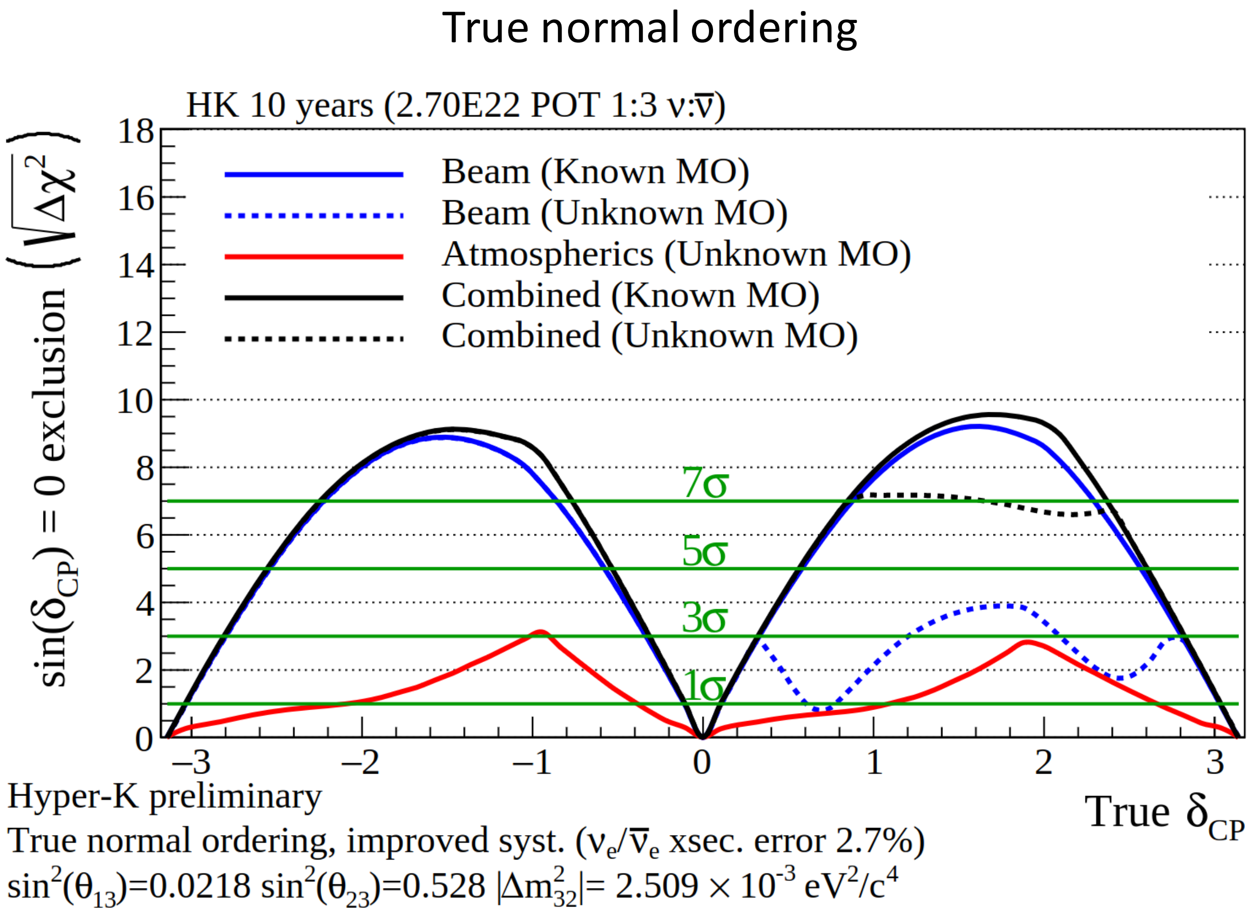
Conclusions

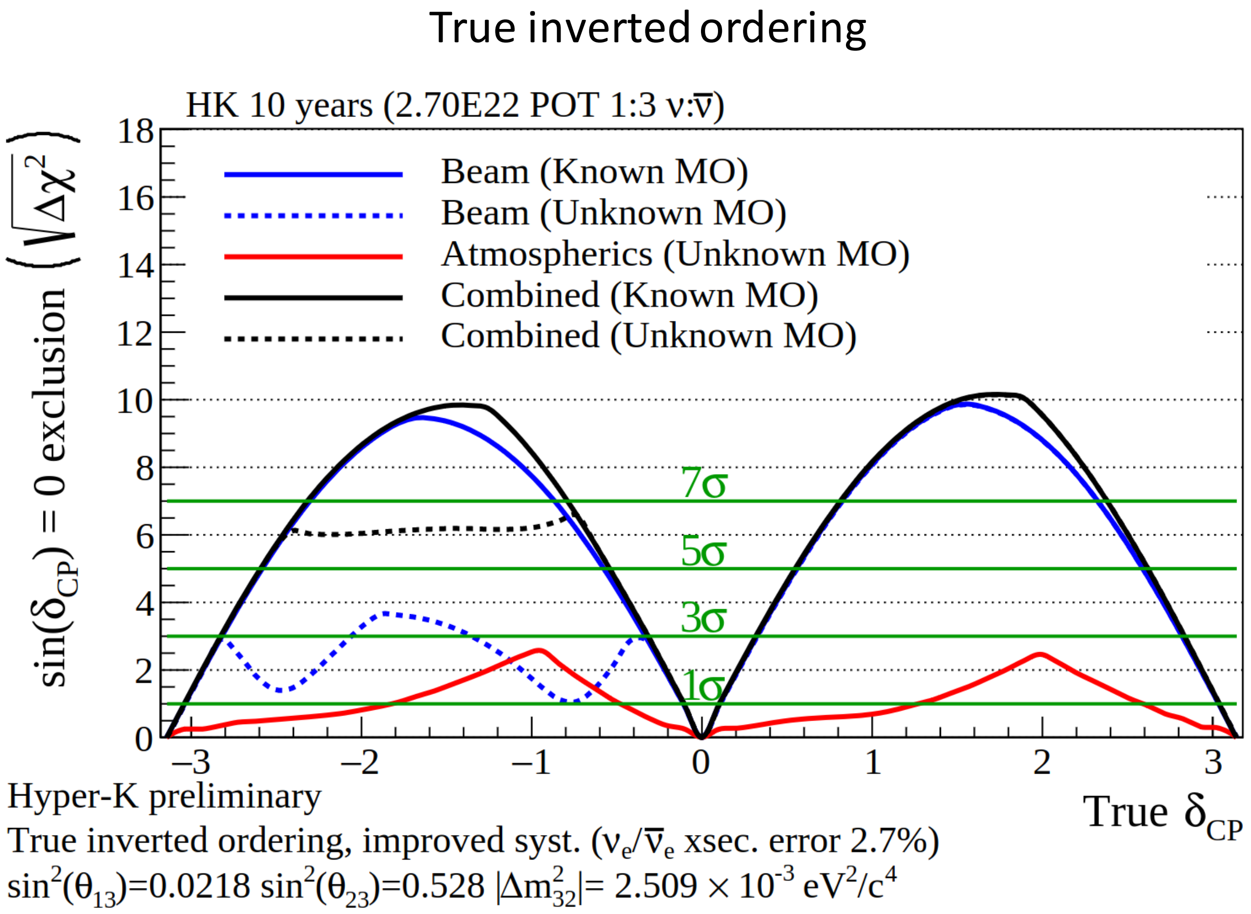
- HK will provide great sensitivity to neutrino oscillation parameters:
  - 5σ CP violation sensitivity for >60% of true δ_{CP} values
  - 6-20 degree precision on measurement of δ_{CP}, depending on true value
  - 3σ rejection of wrong-octant of θ_{23} for $\sin^2\theta_{23} < 0.47$ or $\sin^2\theta_{23} > 0.55$
  - 0.4% precision on Δm^2_{32} measurement
- Ability to constrain systematic uncertainties will be key to precise measurement
- Development of analysis tools for HK is ongoing
- Construction is progressing on track for 2027 data taking



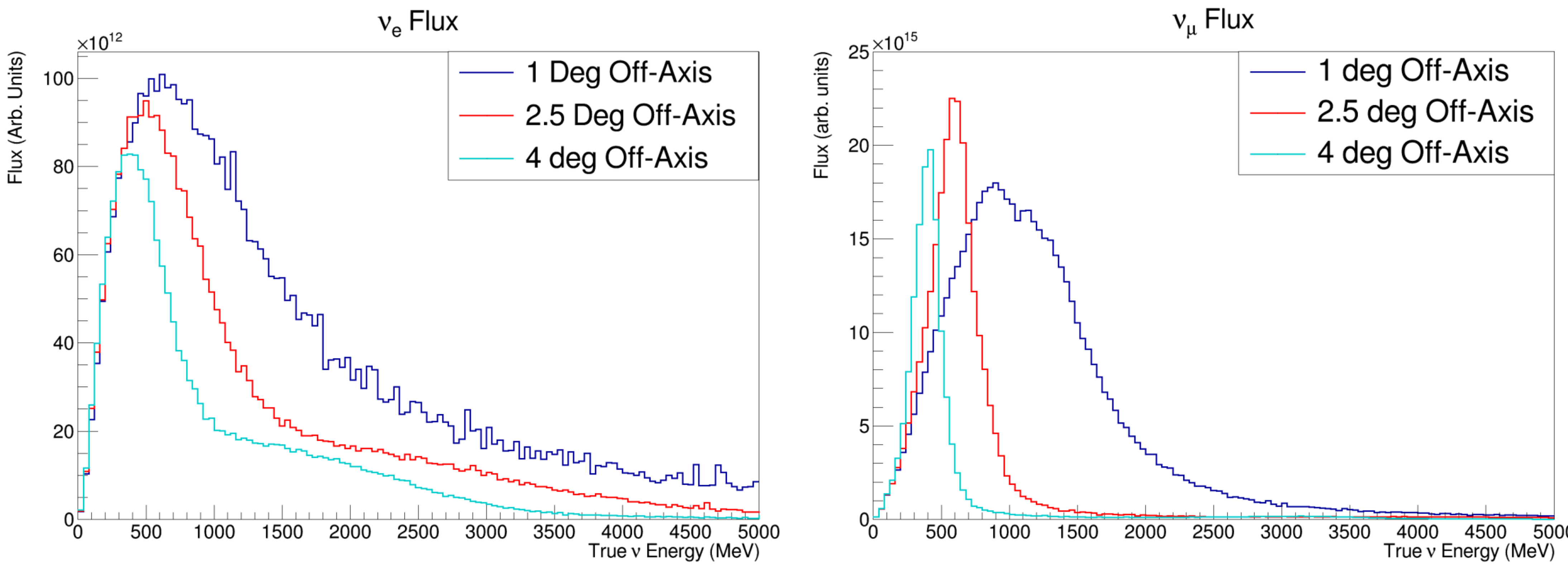
Backups

CP sensitivity unknown MO

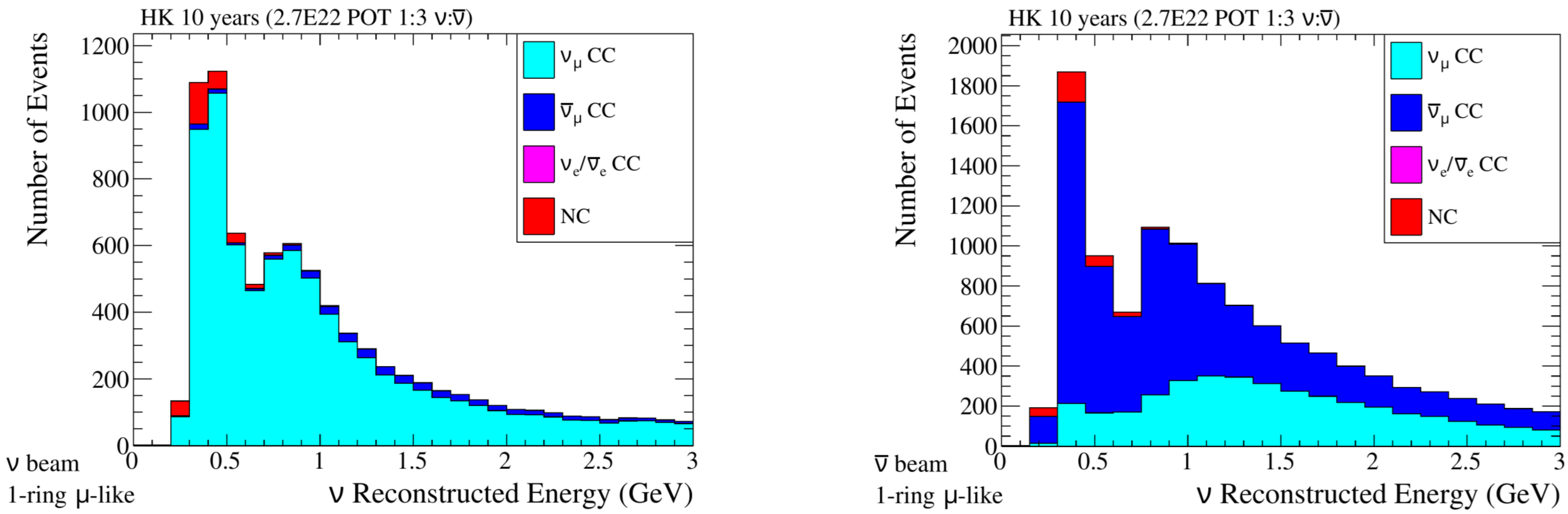




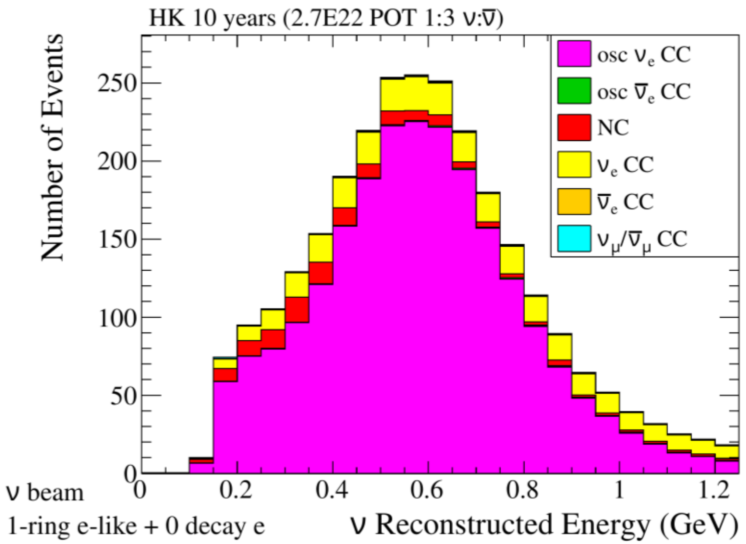
IWCD Fluxes

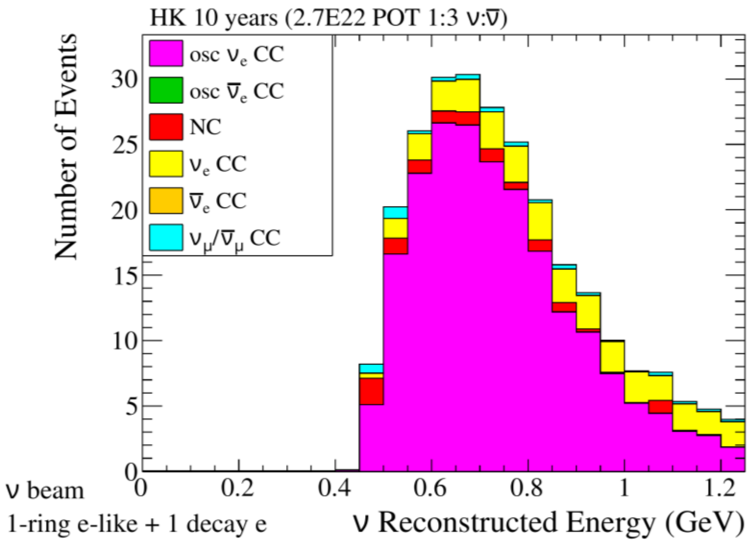

ν_e Flux
$\times 10^{12}$
Flux (Arb. Units)
0
20
40
60
80
100
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
True ν Energy (MeV)
1 Deg Off-Axis
2.5 Deg Off-Axis
4 deg Off-Axis
ν_μ Flux
$\times 10^{15}$
Flux (arb. units)
0
5
10
15
20
25
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
True ν Energy (MeV)
1 deg Off-Axis
2.5 deg Off-Axis
4 deg Off-Axis

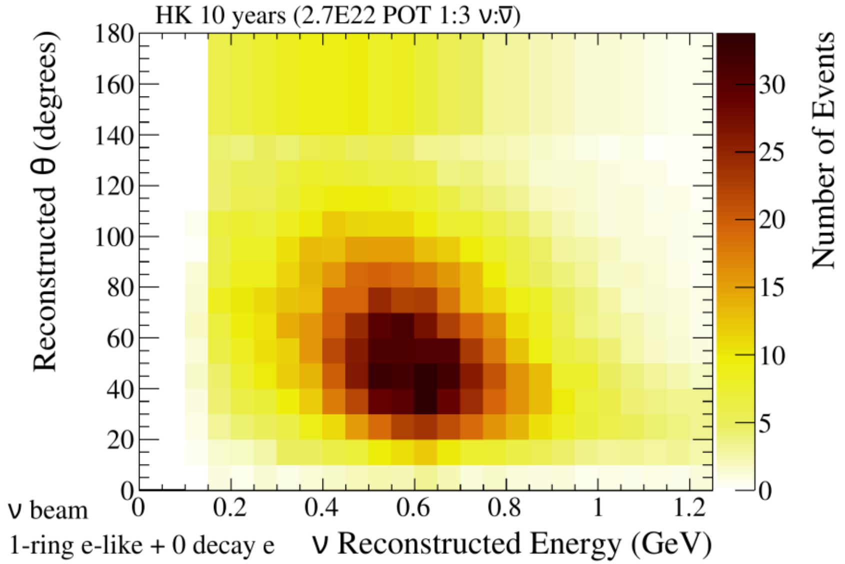
NuMu appearance spectra

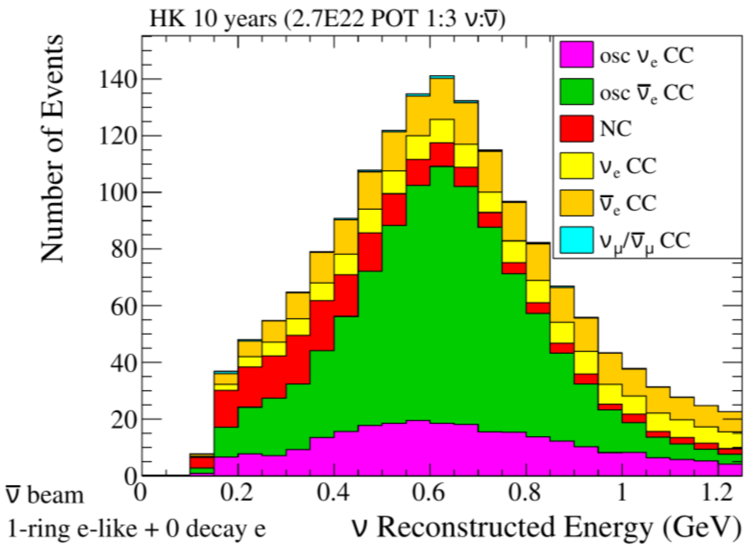


NuE appearance spectra









NuMu oscillation probability

$$P\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu\right) \approx 1 - 4\left((s_{23}^2 c_{13}^2)(1 - s_{23}^2 c_{13}^2)\right) \sin^2\left(\Delta_{32} + \Delta_{21}\frac{s_{12}^2 c_{23}^2}{1 - s_{23}^2 c_{13}^2}\right)$$

$$+ \mathcal{O}\left(a^2, \Delta_{21}\right)$$

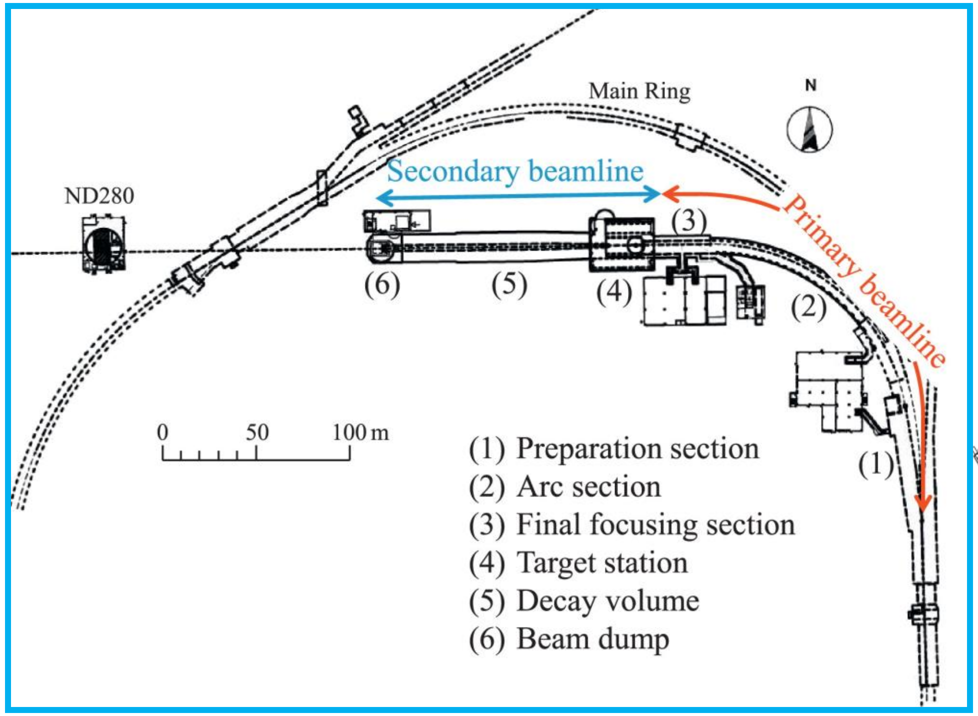
$$\approx 1 - \sin^2 2\theta_{23} \sin^2\left(\Delta_{32}\right)$$

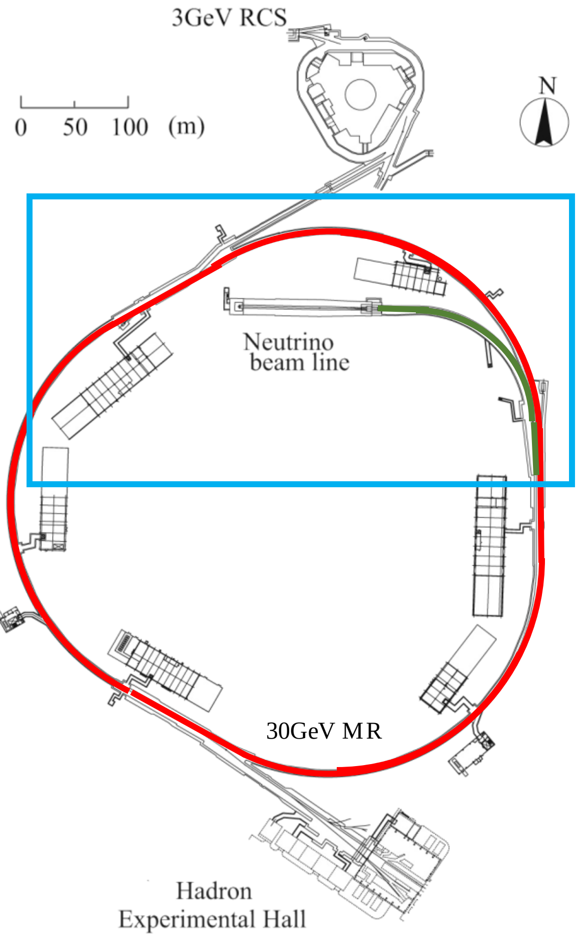
NuE Appearance Probability

$$
\begin{aligned}
P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e\right) \approx\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}\mp a)}{(\Delta_{31}\mp a)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\cos\theta_{12}\frac{\sin(\Delta_{31}\mp a)}{\Delta_{31}\mp a}\Delta_{31}\frac{\sin a}{a}\Delta_{21}\cos\Delta_{31}\cos\delta_{CP} \\
& \mp \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\cos\theta_{12}\frac{\sin(\Delta_{31}\mp a)}{\Delta_{31}\mp a}\Delta_{31}\frac{\sin a}{a}\Delta_{21}\sin\Delta_{31}\sin\delta_{CP} \\
& + \cos^2\theta_{13}\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2 a}{a^2}\Delta_{21}^2
\end{aligned}
$$

J-PARC beam

- 30GeV J-PARC proton main ring
- Intend to run at 1.16 s repetition, up to 1.3 MW
- Three 320 kA focusing horns





doi.org/10.1016/j.nima.2013.06.105