Hyper-Kamiokande

Addressing the challenge of neutrino interaction uncertainties in Hyper-Kamiokande

LPNHE PARIS

SORBONNE UNIVERSITÉ

Claire Dalmazzone, 13th October 2023

On behalf of Hyper-Kamiokande Collaboration

22nd International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

Procida (Italy), October 11-13, 2023

INFN NAPOLI

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

Università degli Studi della Campania Luigi Vanvitelli

Comune di Procida

Contents

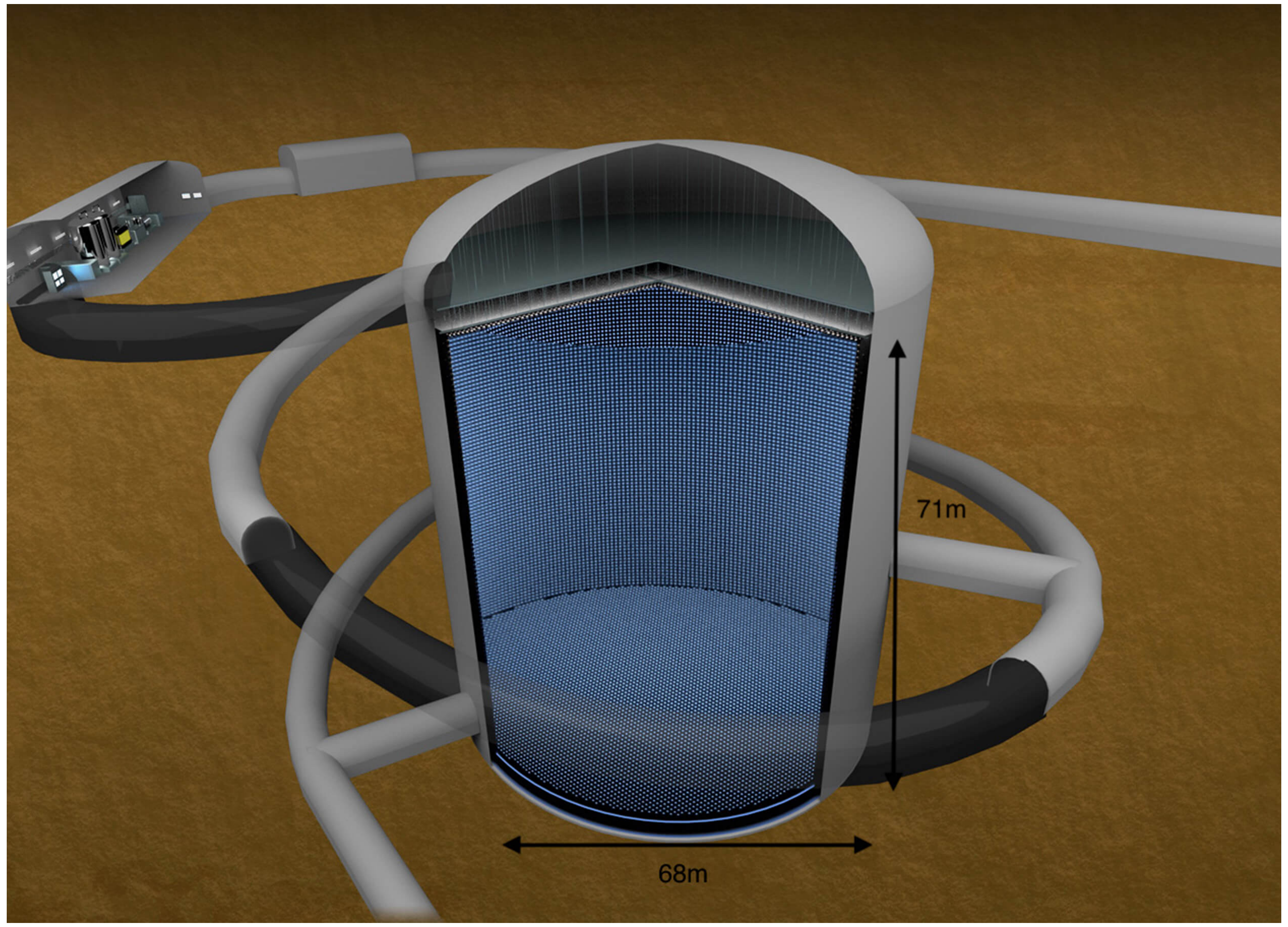
- Hyper-Kamiokande experiment
- HK long baseline program
- Neutrino interaction in HK
- HK plan to reduce systematic uncertainties

Hyper-Kamiokande experiment

The detector

- Next generation water Cherenkov neutrino detector in Japan.
  In construction, start data-taking in 2027
- 260kt of water: fiducial volume ~ 8 times SK!

Excavation reached center of cavern dome in July

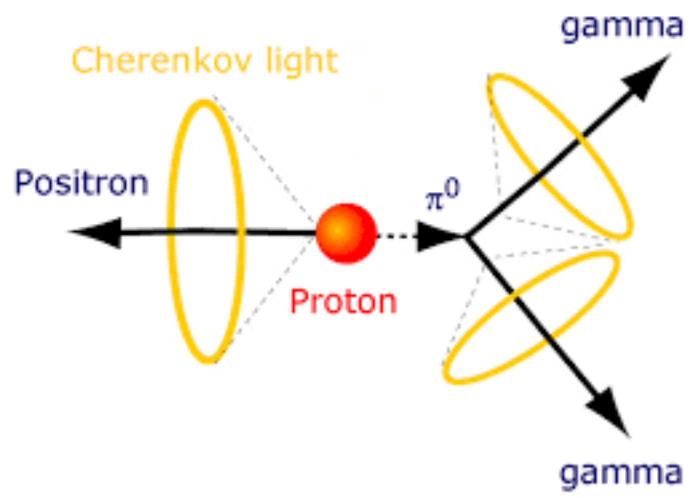


The Hyper-Kamiokande detector

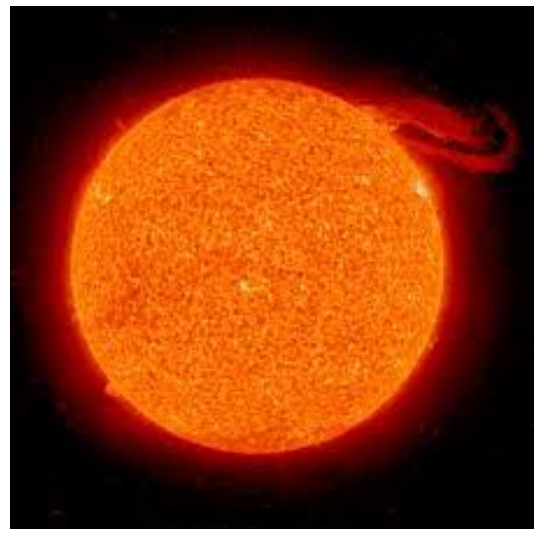
See Katsuki Hiraide's talk

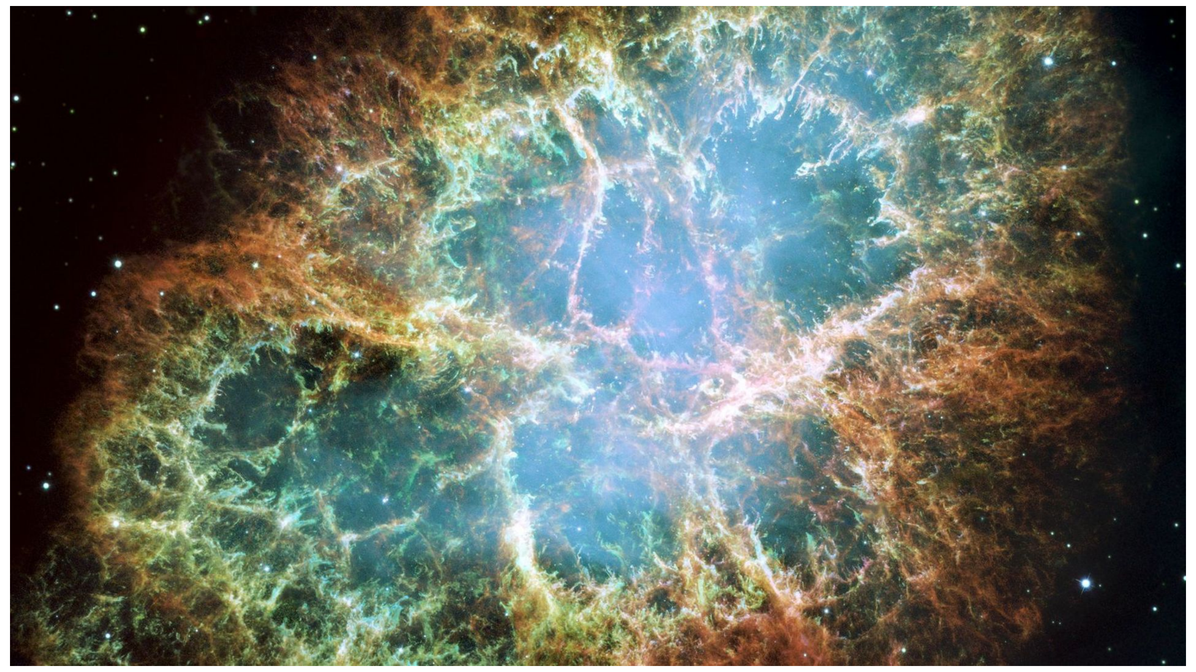
Hyper-Kamiokande experiment

A vast physics program

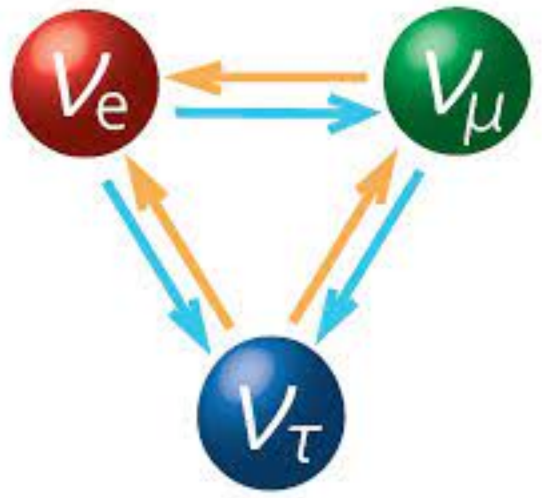


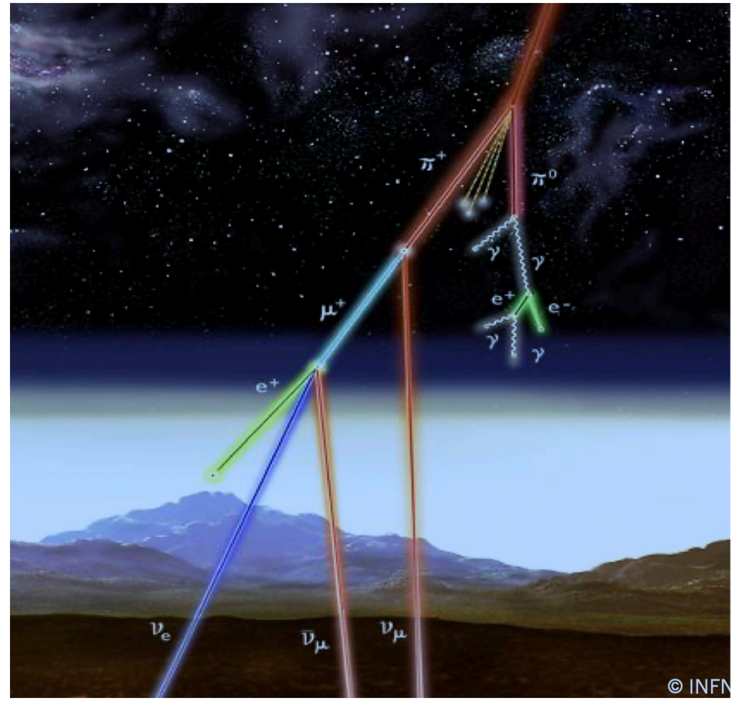
- Nucleon decay: evidence for a Grand Unified Theory
- Neutrino astrophysics: Supernovae and Diffuse Supernovae Background
- Solar neutrinos





- Neutrino oscillation: atmospheric + accelerator neutrinos





See Katsuki Hiraide's talk

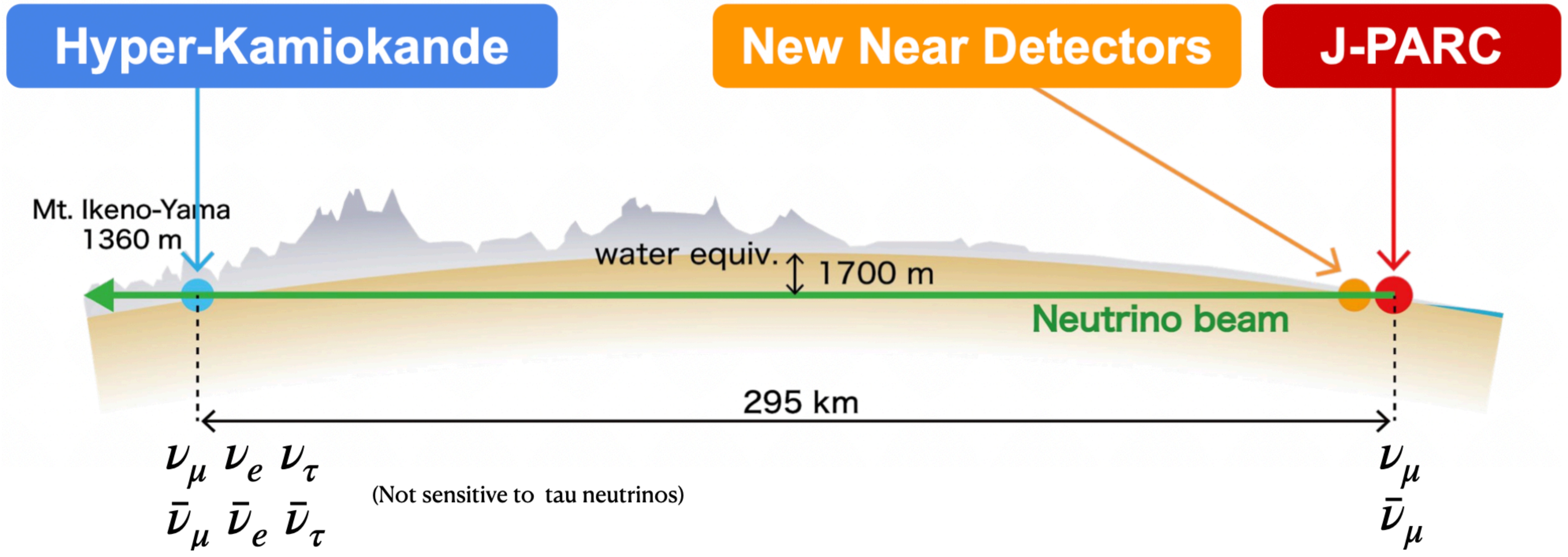
Long baseline program

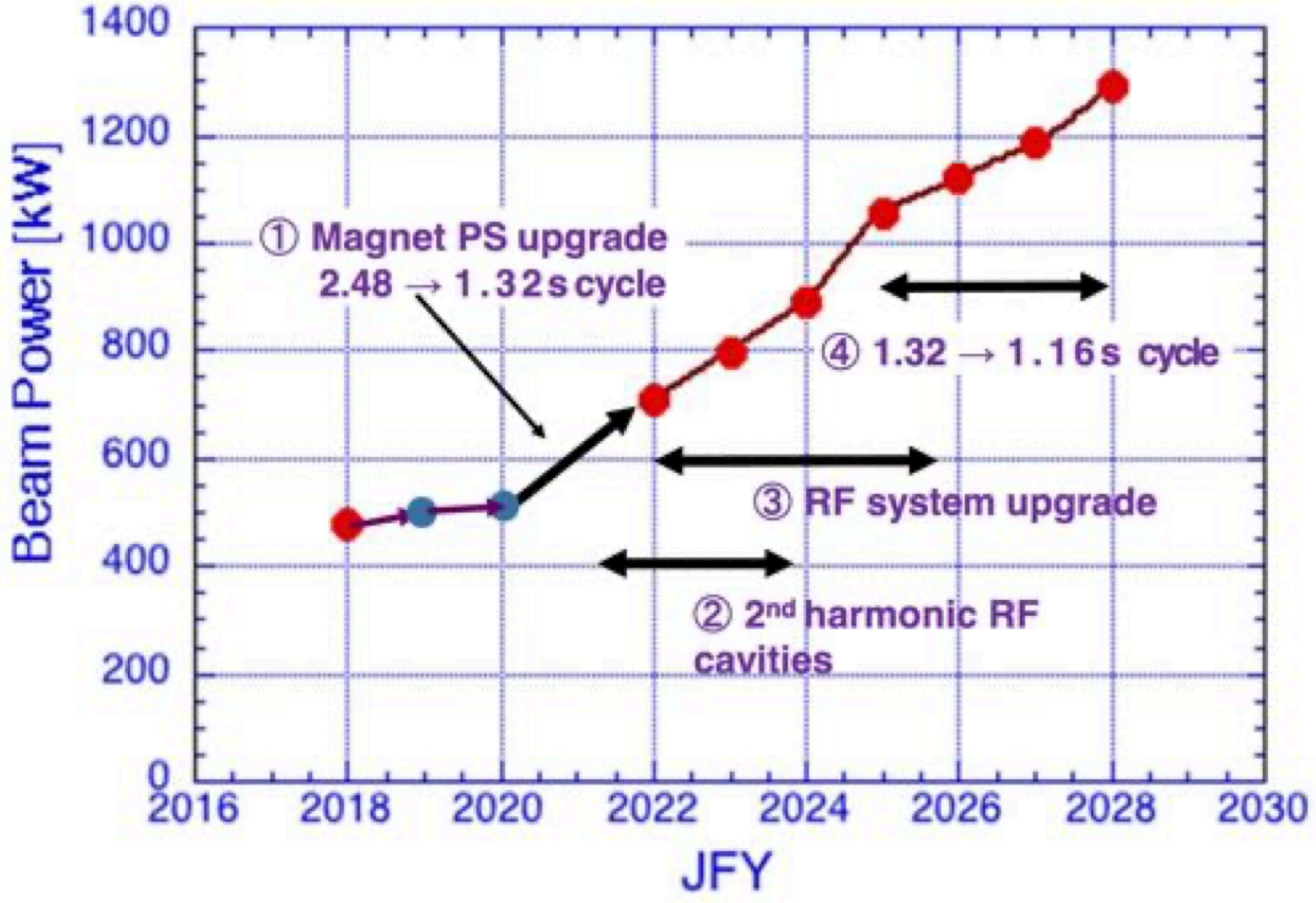
Overview

Same baseline as T2K **with upgrades**:

✓ ν_μ ($\bar{\nu}_\mu$) beam produced at J-PARC accelerator facility: flux peaked at 600 MeV in HK/SK directions

More intense beam: 750 kW → 1.3MW





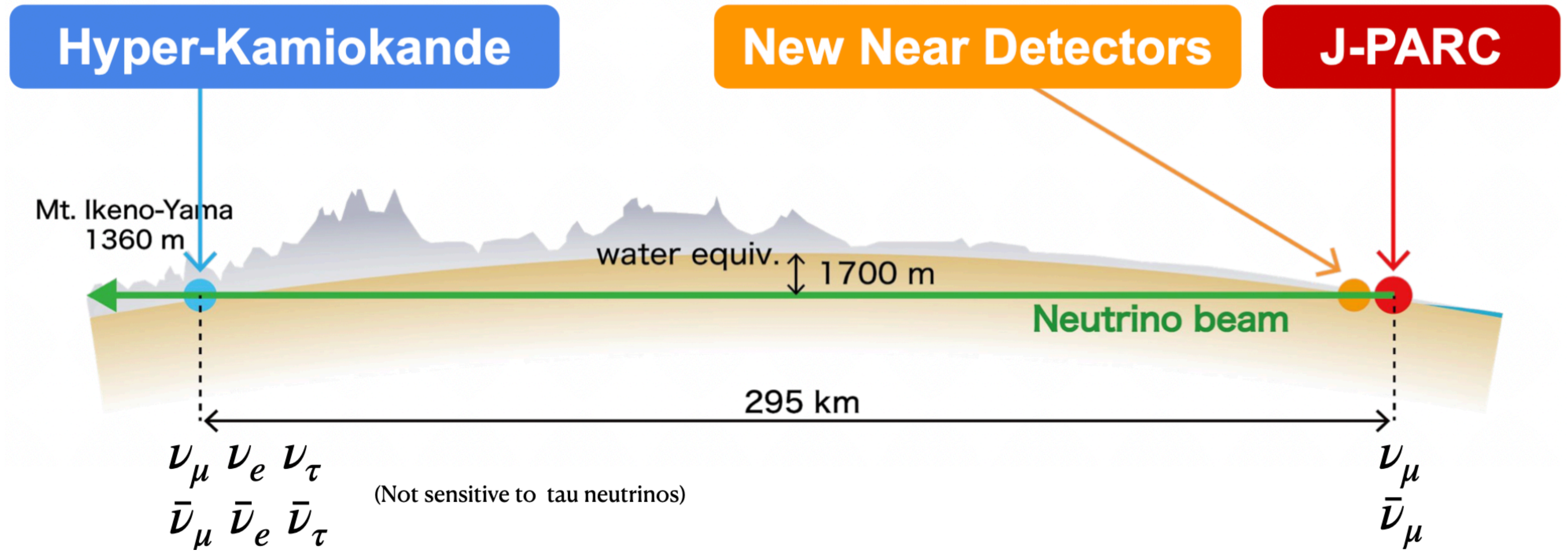
Credit: Megan Friend, NuFact 2021

Long baseline program

Overview

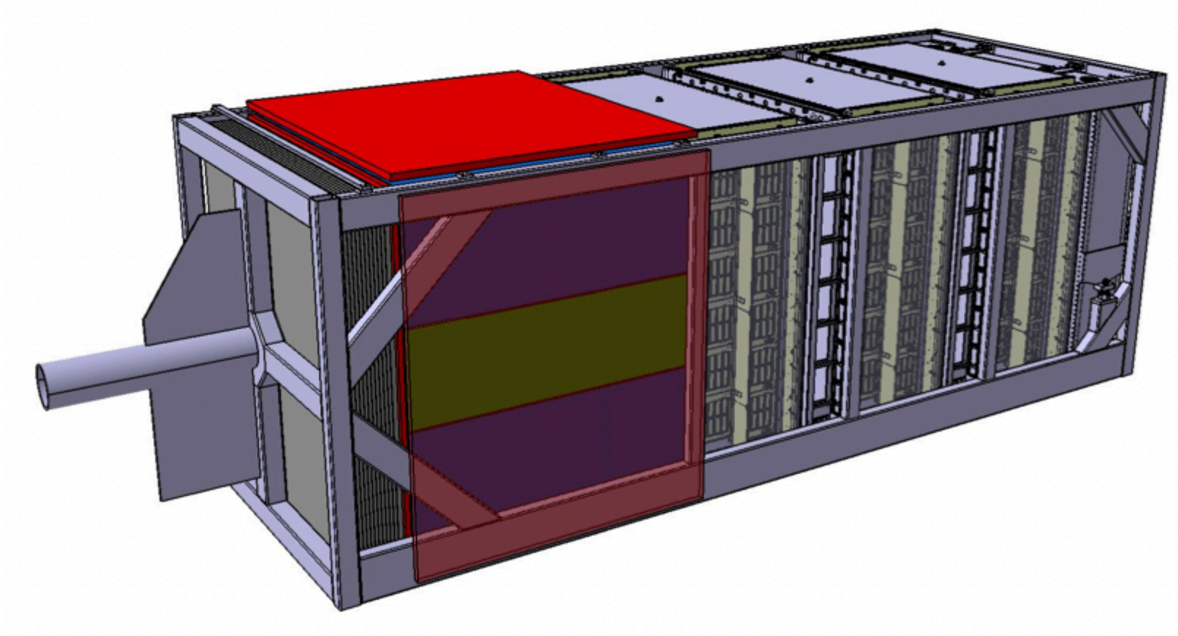
Same baseline as T2K **with upgrades**:

✓ ν_μ ($\bar{\nu}_\mu$) beam produced at J-PARC

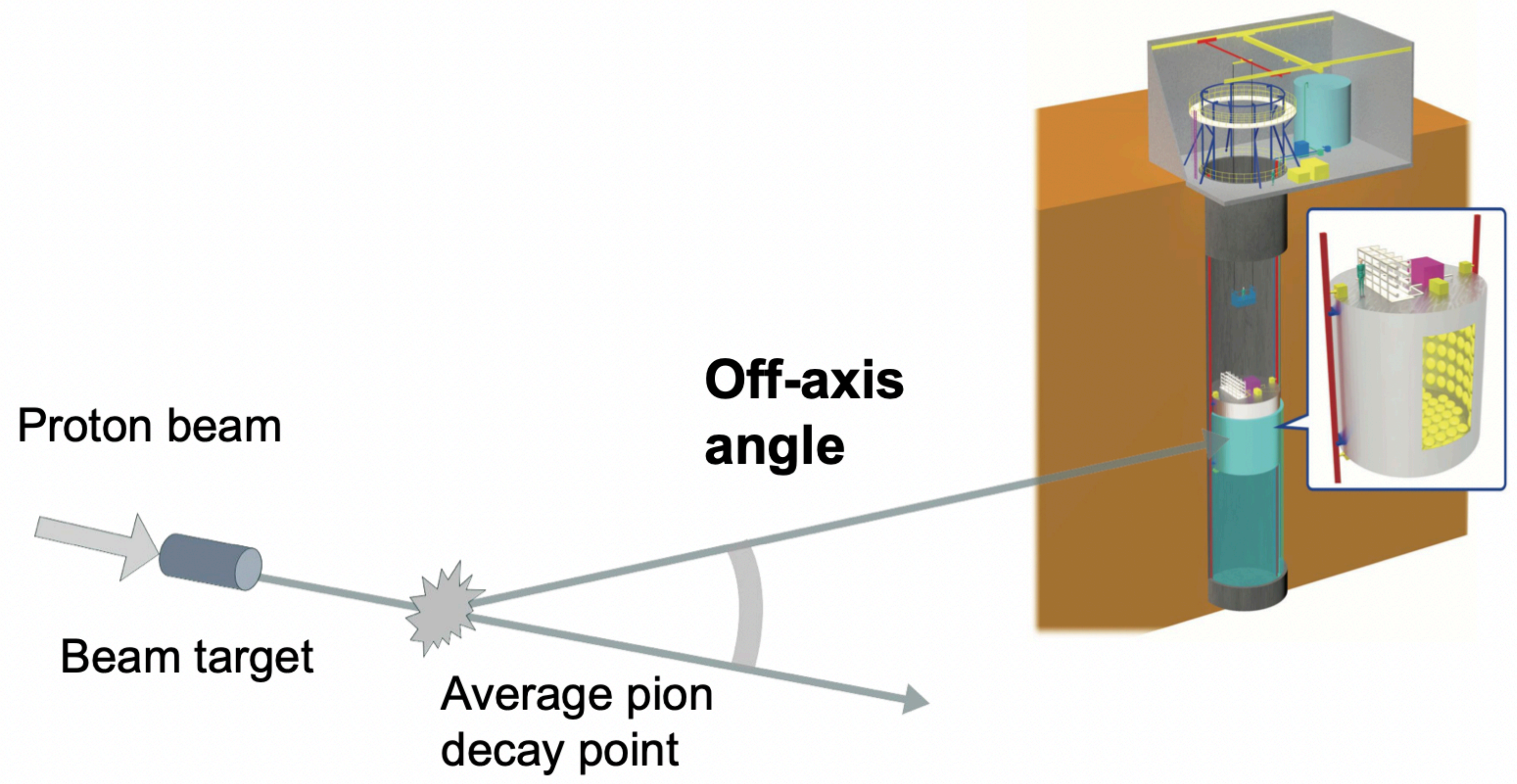


✓ Near detectors measure flux and interaction cross-section before oscillation

Upgraded ND280 (280m) + new Intermediate Water Cherenkov Detector (IWCD) at ~1km



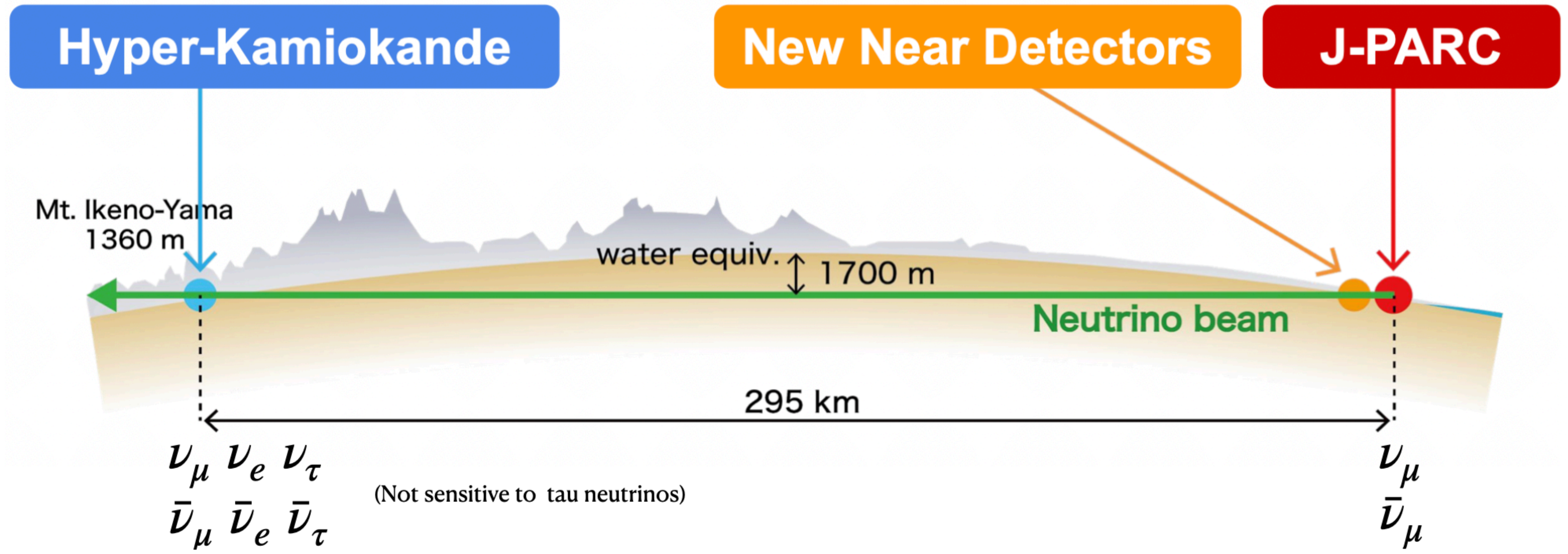
ND280 after current upgrade:
larger volume + better angular coverage



IWCD: vertically movable (varying off-axis angle)

Long baseline program

Overview



Same baseline as T2K **with upgrades**:

✓ ν_μ ($\bar{\nu}_\mu$) beam produced at J-PARC

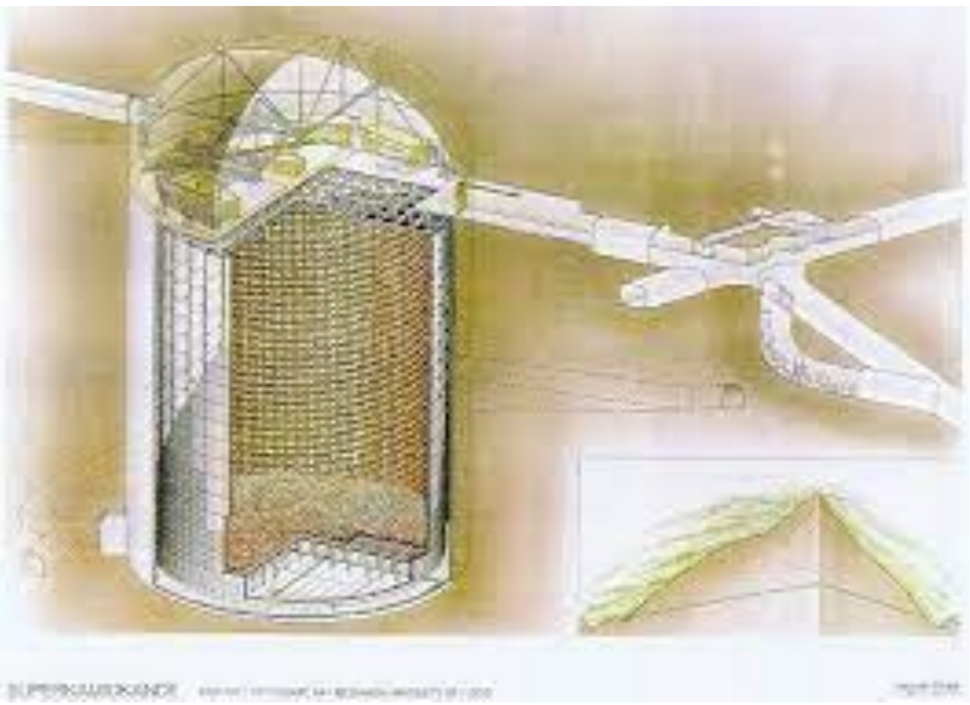
✓ Near detectors measure flux and interaction cross-section before oscillation

✓ Far detector (2.5° off-axis)

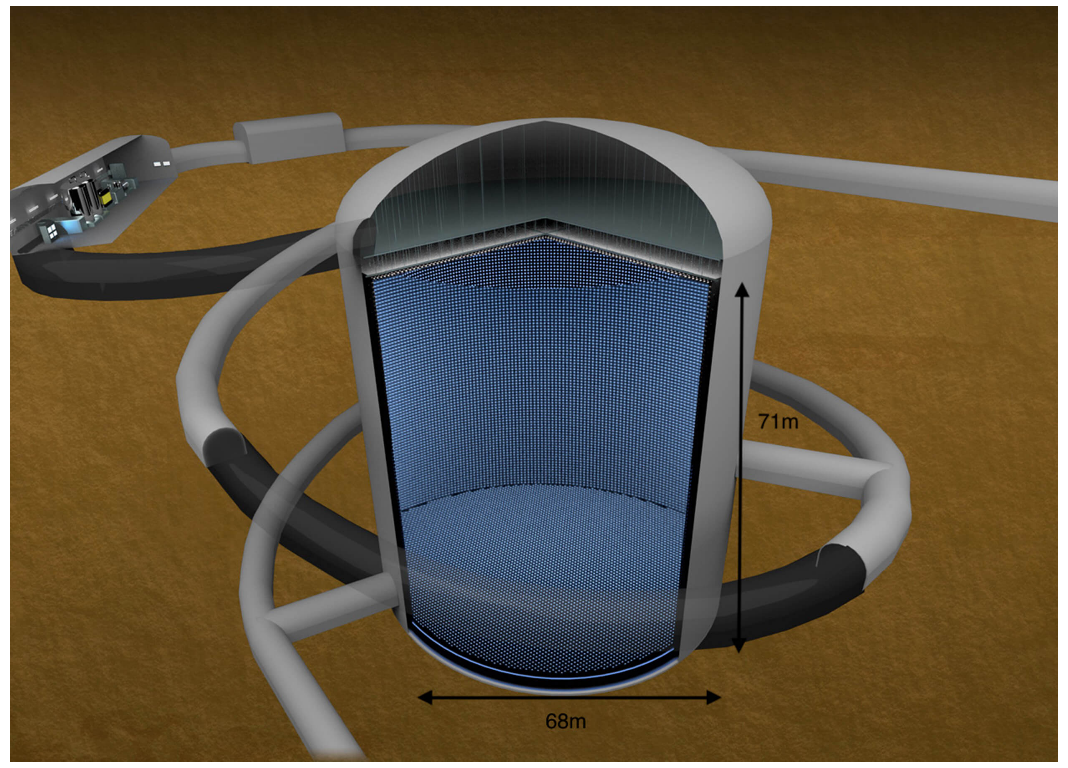
ν_e ($\bar{\nu}_e$) appearance

ν_μ ($\bar{\nu}_\mu$) disappearance

HK fiducial volume 8 times larger than SK



SK: 39m×41m



HK: 68m×71m

Long baseline program

Hyper-Kamiokande

Physics goal

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

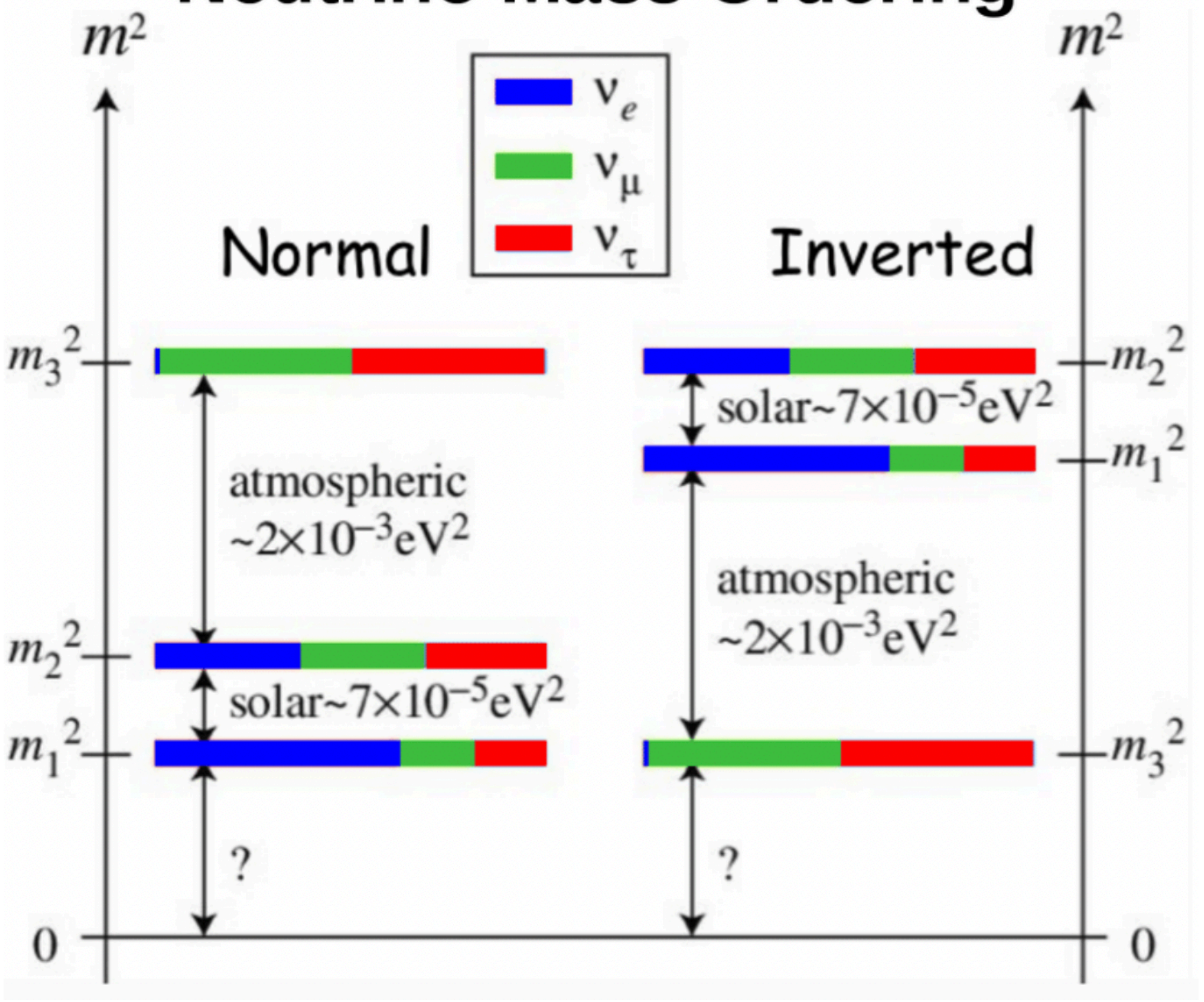
LBL program sensitive to combination of Δm^2_{32}, θ_{23}, δ_{CP} and θ_{13}

Some questions remain unanswered:

- ✓ Mass ordering?
- ✓ θ_{23} octant?
- ✓ CP violation?

Sensitivity with matter effects:
use atmospheric neutrinos

Neutrino Mass Ordering



Long baseline program

Physics goal

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta_{CP}}\\0&1&0\\-\sin\theta_{13}e^{i\delta_{CP}}&0&\cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

LBL program sensitive to combination of Δm^2_{32}, θ_{23}, δ_{CP} and θ_{13}

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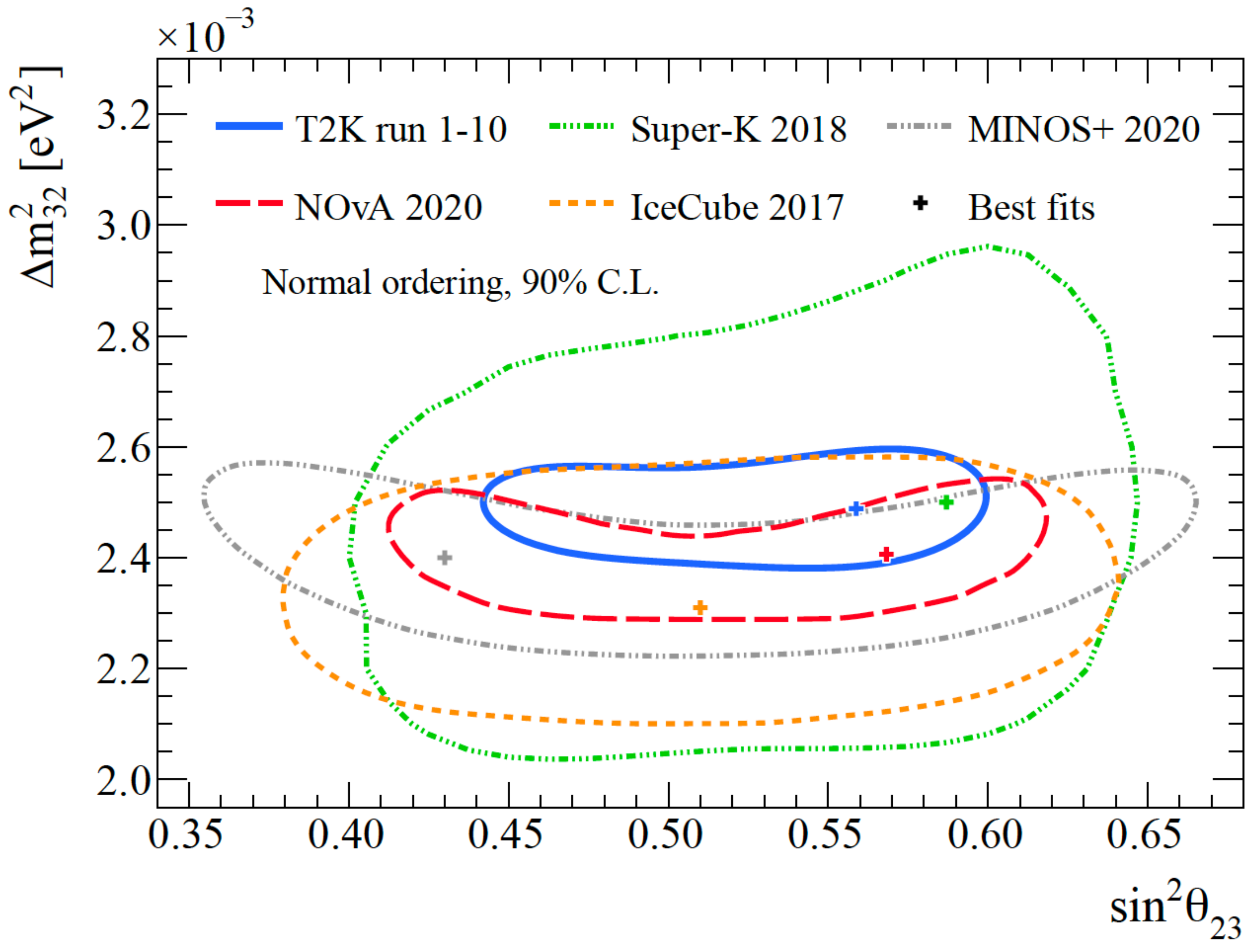
- ✓ CP violation?

Comparison of 90% confidence regions in $\sin^2\theta_{23}-\Delta m^2_{32}$ between leading experiments.



Ref.1 Fig. 37

Long baseline program

Physics goal

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

LBL program sensitive to combination of Δm^2_{32}, θ_{23}, δ_{CP} and θ_{13}

Some questions remain unanswered:

- ✓ Mass ordering?
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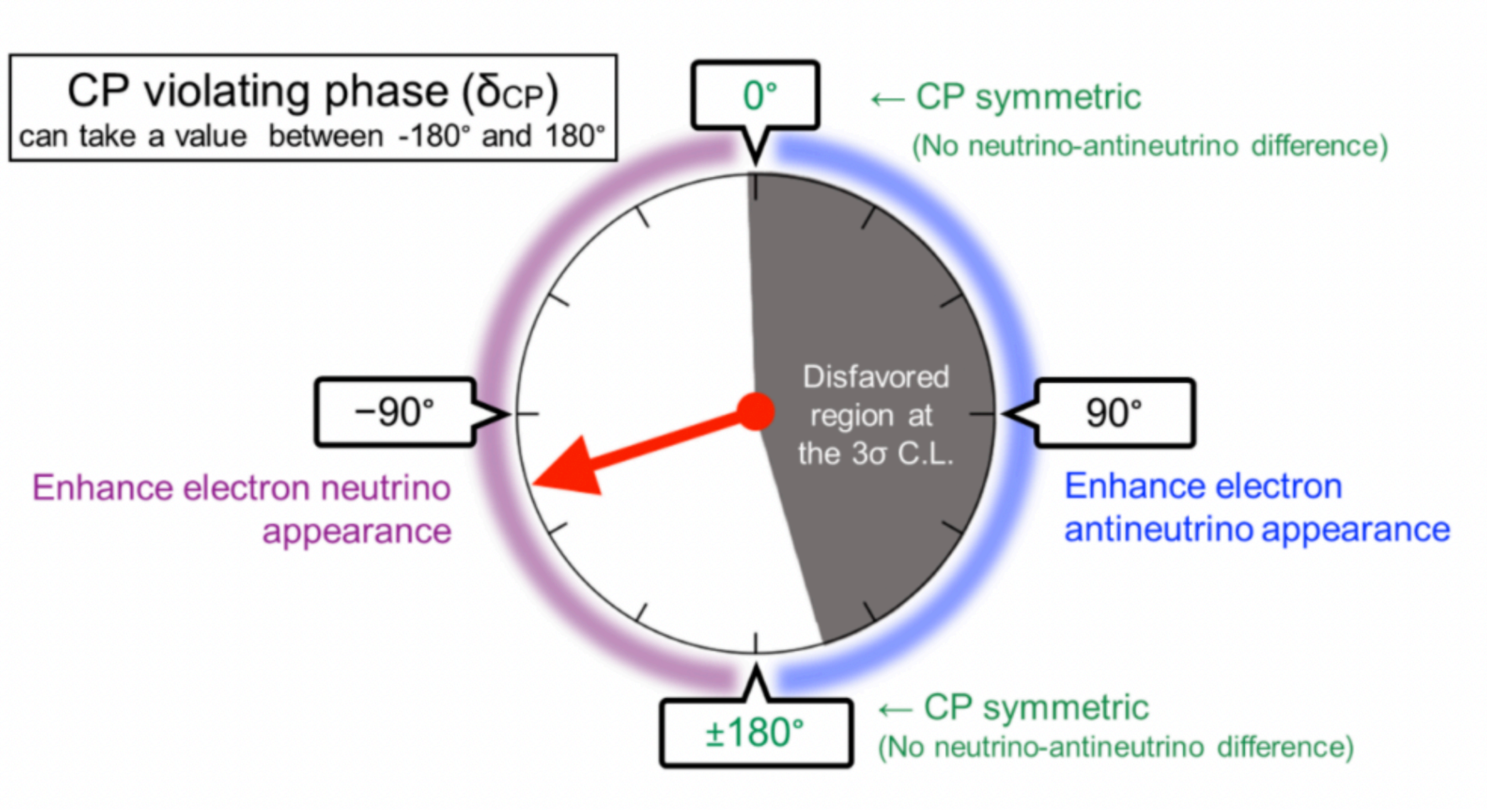
- ✓ CP violation?

Sensitivity with ν_e and $\bar{\nu}_e$ samples



Hint of maximal CP violation with enhanced ν_e appearance from T2K.

Credit: https://j-parc.jp/c/en/press-release/2020/04/16000517.html

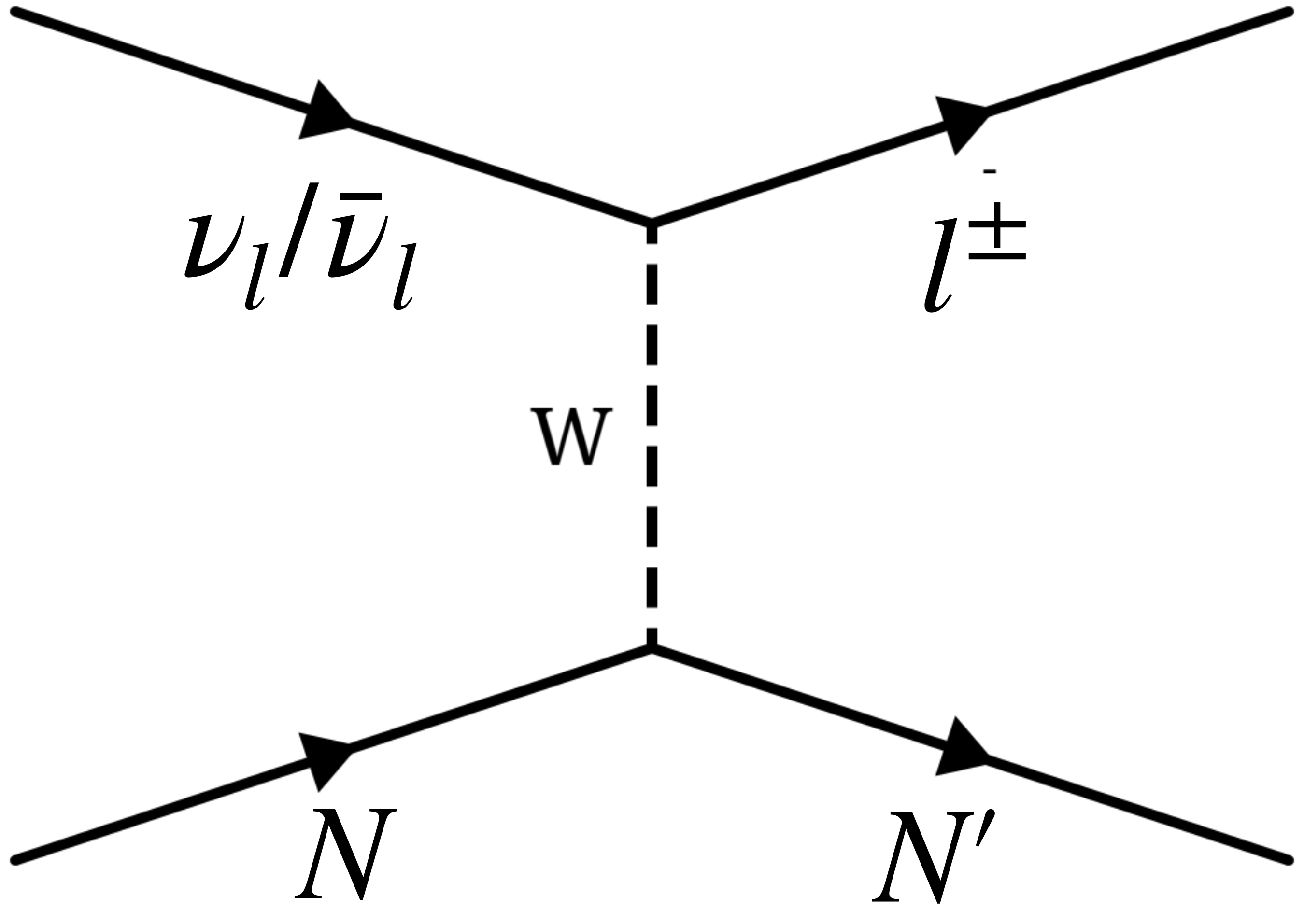
Long baseline program

Oscillation parameters measurements

The **oscillation/survival probability** depends on the **energy** and the **oscillation parameters**.
To measure the oscillation parameters, we need to:

- **Count the $\nu_e(\bar{\nu}_e)/\nu_\mu(\bar{\nu}_\mu)$**
- **Measure their energies**

At 600MeV, the most common neutrino interaction is the **Charged Current Quasi-Elastic**



$$E_\nu^{rec} = \frac{(M_n - E_b)E_l - m_l^2/2 + m_nE_b - E_b^2/2 + (m_p^2 - m_n^2)/2}{M_n - E_b - E_l + p\cos\theta}$$

Reconstructed neutrino energy from measured lepton energy based on CCQE interaction with one ejected nucleon.

But the reality is more complex…

See Hayato-san's talk

Long baseline program

Oscillation parameters measurements

The **oscillation/survival probability** depends on the **energy** and the **oscillation parameters**.
To measure the oscillation parameters, we need to:

- Count the $\nu_e(\bar{\nu}_e)/\nu_\mu(\bar{\nu}_\mu)$
- Measure their energies

Five event samples* are considered:

- ν beam, 1-ring μ-like
- $\bar{\nu}$ beam, 1-ring μ-like
- ν beam, 1-ring e-like
- $\bar{\nu}$ beam, 1-ring e-like
- ν beam, 1-ring e-like + 1 decay e

From the decay chain of a pion produced during the neutrino interaction

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* Based on T2K event samples in latest published results (ref. 1)

Long baseline program

Sources of uncertainties

Flux in detector

Interaction cross-section

Event rate measured in detector

$$N = F \times \sigma \times \epsilon$$

Detector efficiency

Three sources of systematic effects:

- Neutrino Flux
- Neutrino interaction
- Detector efficiency

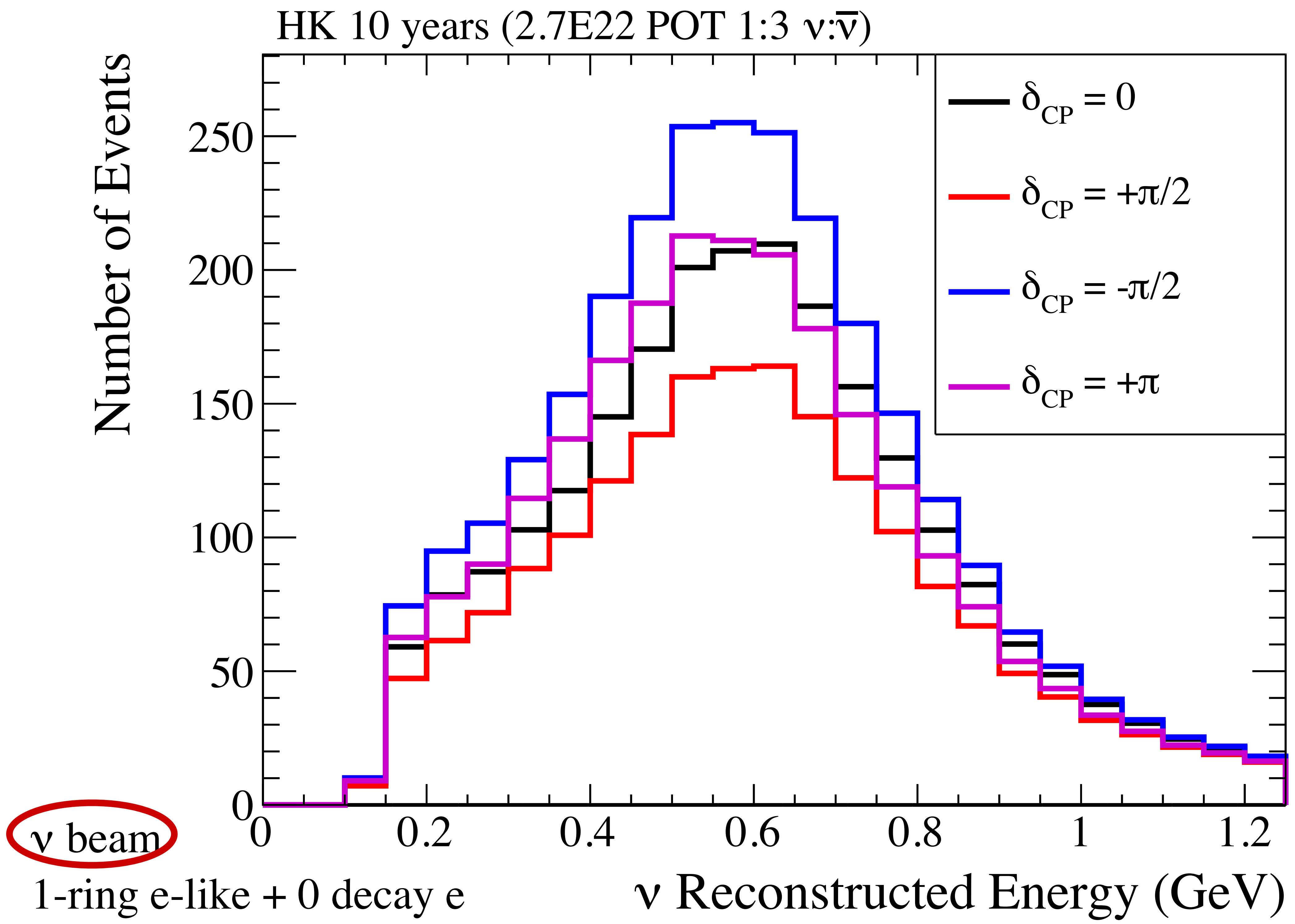
Simultaneously constrained at the near detectors + external experimental constraints*

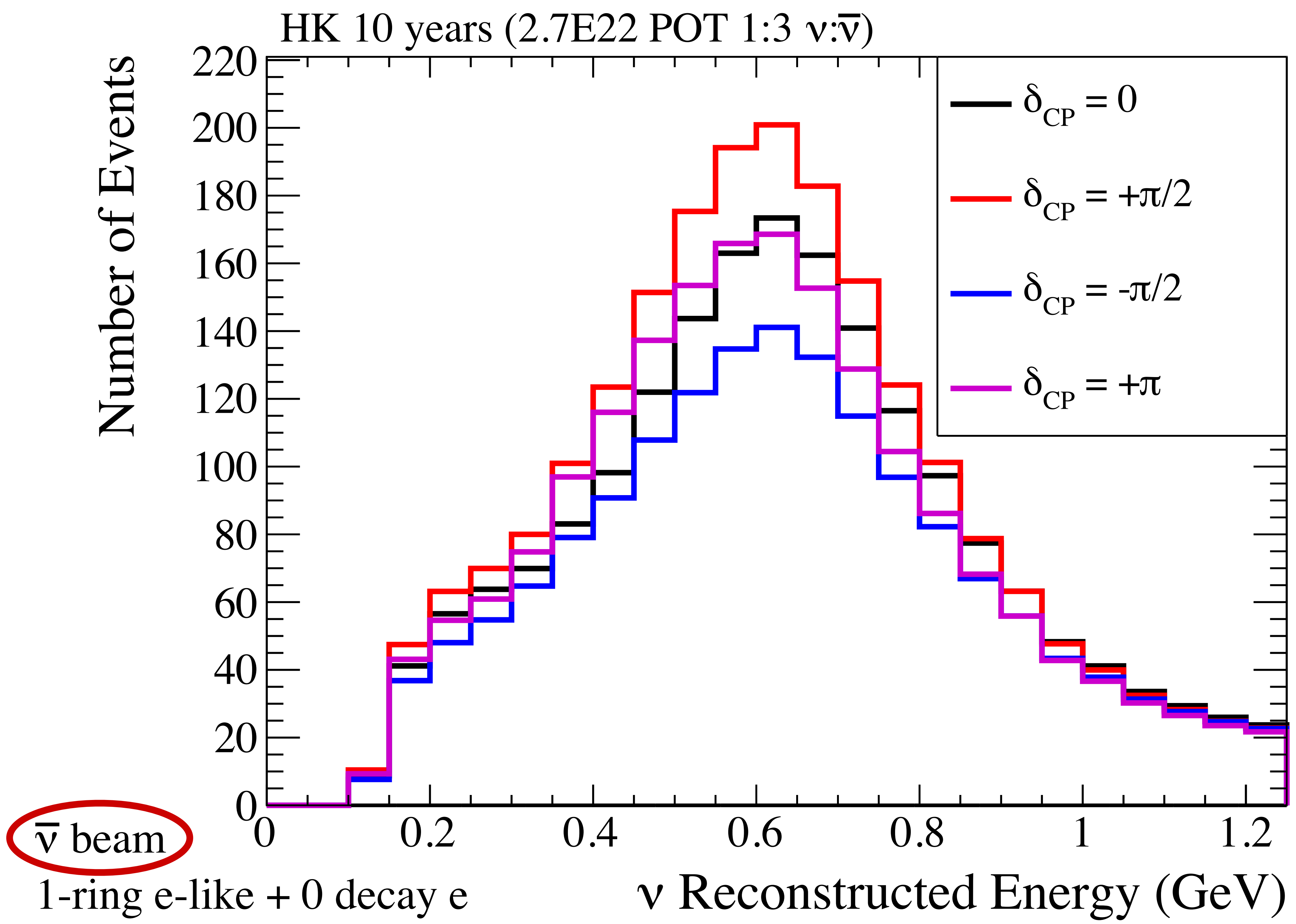
* e.g.: see Lu Ren’s talk on NA61/SHINE neutrino program to reduce flux uncertainties due to hadron production

Long baseline program

Oscillation parameters measurements

Expected event rates in e-like samples: impact of δ_{CP}

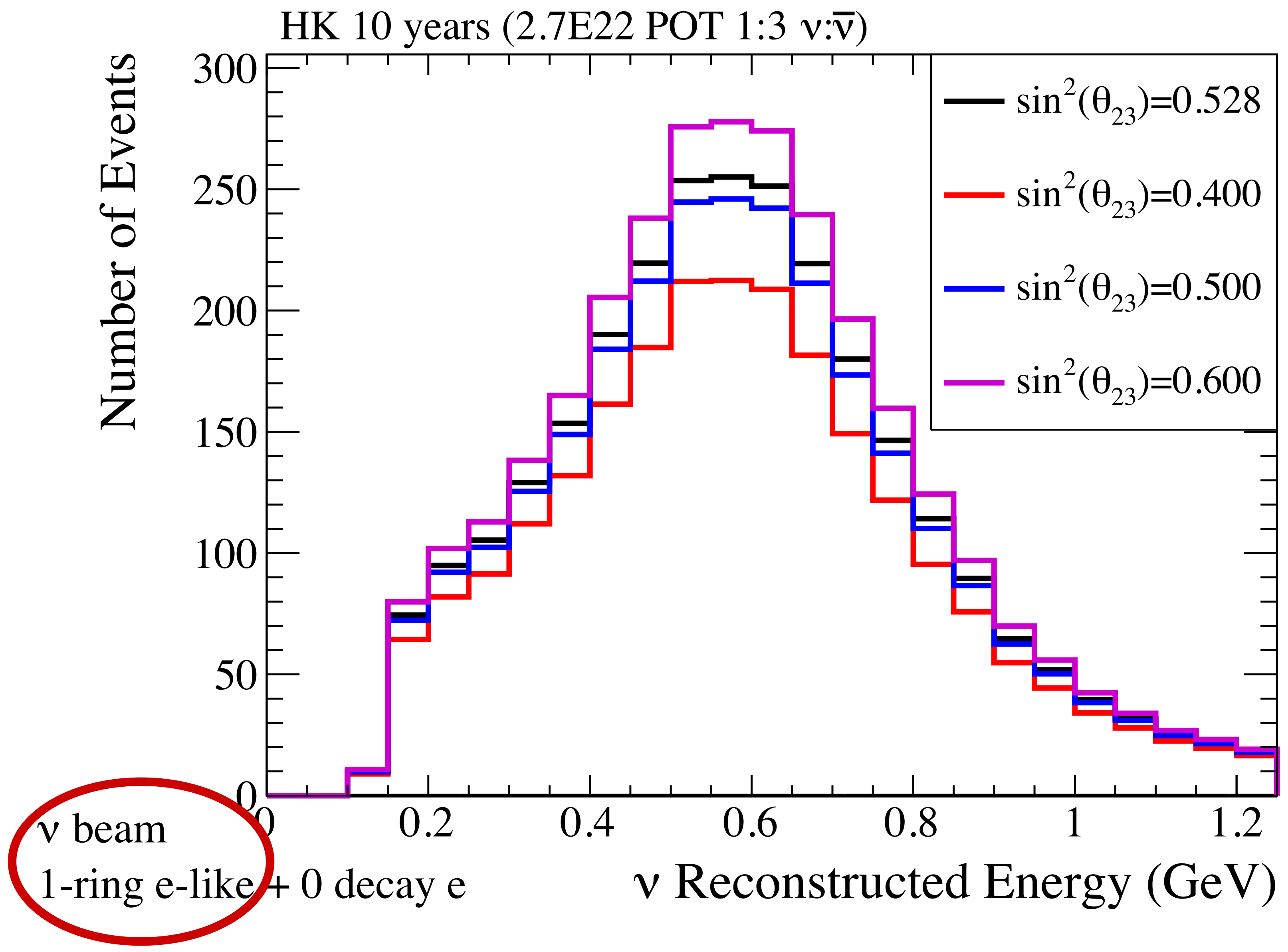


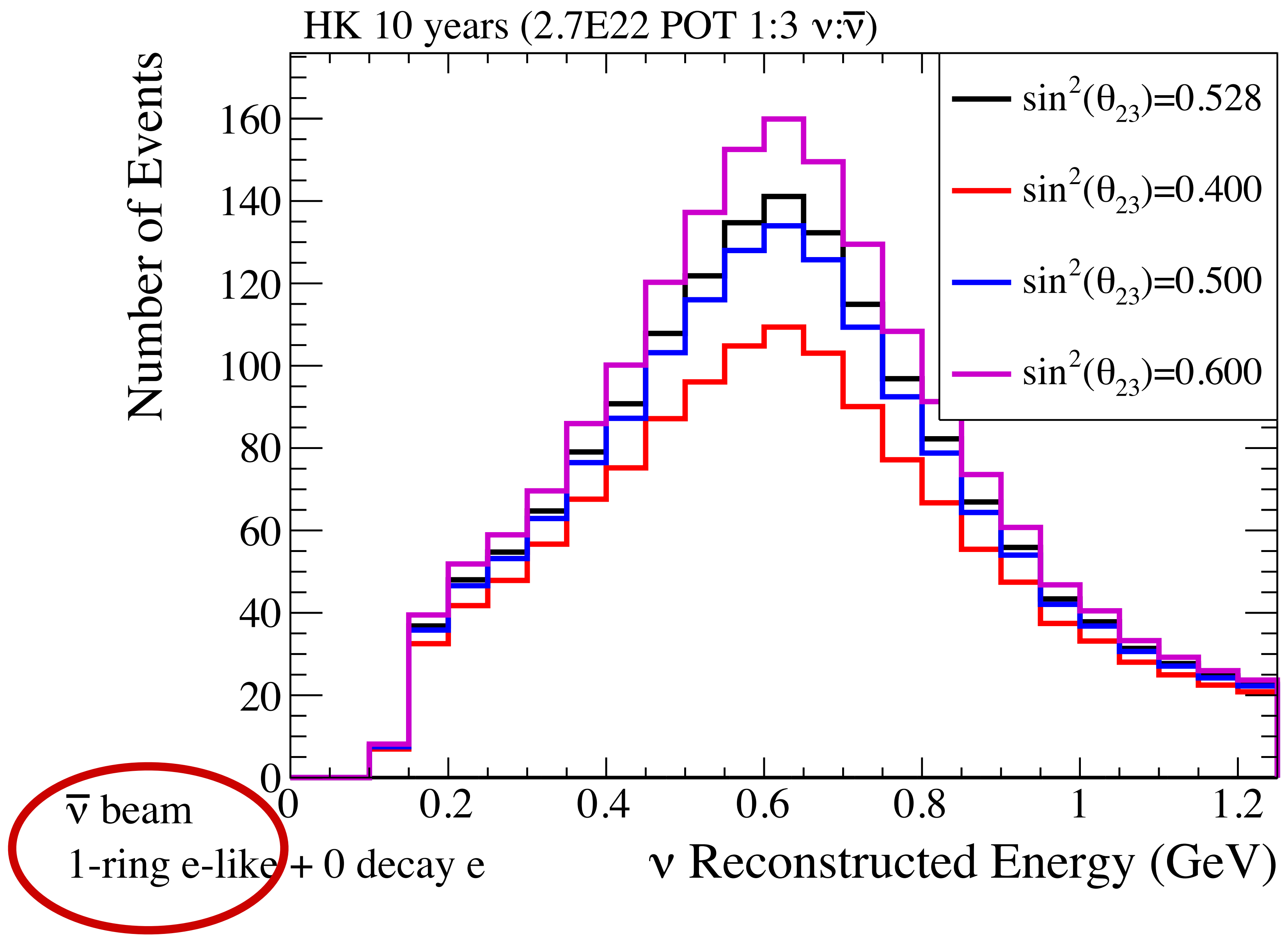


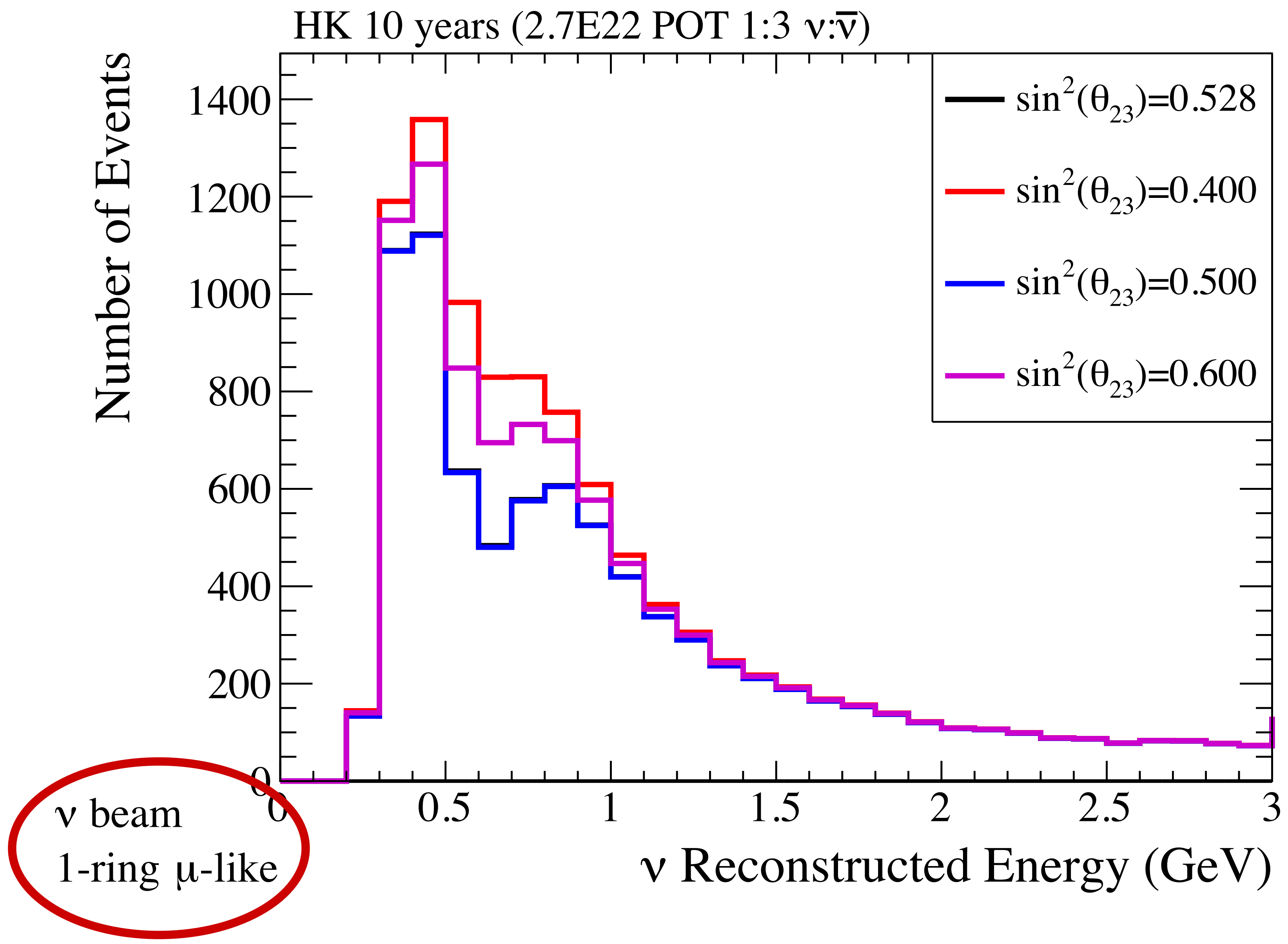
Long baseline program

Oscillation parameters measurements

Expected event rates: impact of $\sin^2\theta_{23}$



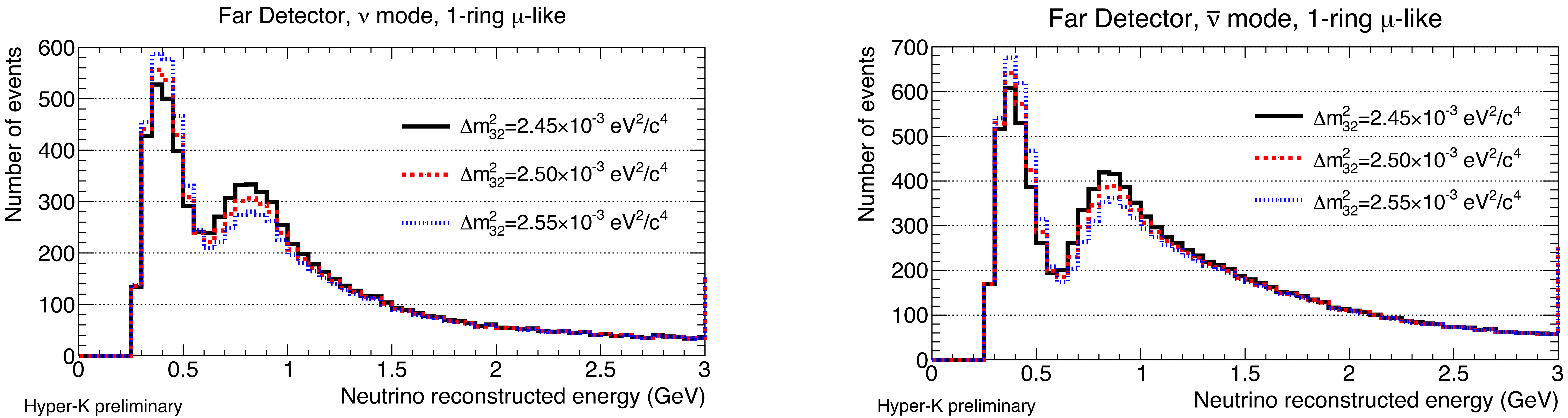




Long baseline program

Oscillation parameters measurements

Expected event rates in μ-like samples: impact of Δm^2_{32}



Hyper-K preliminary
10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
Normal Ordering, $\sin^2\theta_{13}$=0.0218, $\sin^2\theta_{23}$=0.528, δ_{CP}=-1.601

Hyper-K preliminary
10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
Normal Ordering, $\sin^2\theta_{13}$=0.0218, $\sin^2\theta_{23}$=0.528, δ_{CP}=-1.601

Systematic uncertainties

Expected uncertainty on event rates in each sample at HK with T2K ND280 constraints* on flux+cross-section parameters

	1 ring μ-like		1 ring e-like			
Error source	**ν-mode**	**νbar-mode**	**ν-mode CCQE-like**	**νbar-mode CCQE-like**	**ν-mode CC1π-like**	**ν-/νbar-mode CCQE-like**
Flux + Cross section	3,27 %	2,95 %	4,33 %	4,37 %	4,99 %	4,52 %
Detector + FSI + SI	3,22 %	2,76 %	4,14 %	4,39 %	17,77 %	2,06 %
All systematics	4,63 %	4,10 %	5,97 %	6,25 %	18,49 %	4,95 %

* From 10.1103/PhysRevD.103.112008

Systematic uncertainties

Expected uncertainty on event rates in each sample at HK with Improved ND constraints* on flux+cross-section parameters

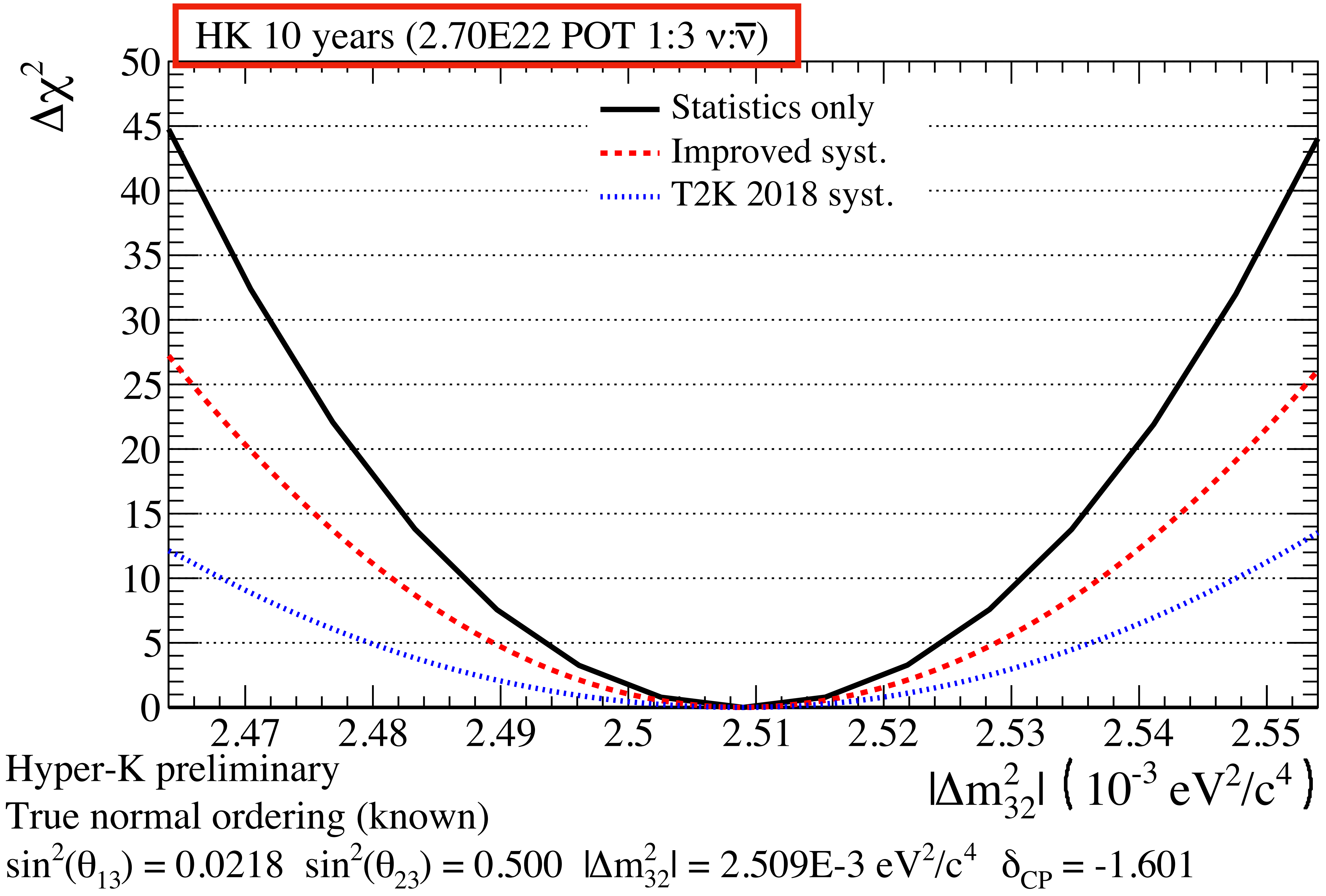
	1 ring μ-like		1 ring e-like			
Error source	**ν-mode**	**νbar-mode**	**ν-mode CCQE-like**	**νbar-mode CCQE-like**	**ν-mode CC1π-like**	**ν-/νbar-mode CCQE-like**
Flux + Cross section	0,81 %	0,72 %	2,07 %	1,88 %	2,21 %	2,28 %
Detector + FSI + SI	1,68 %	1,58 %	1,54 %	1,72 %	5,21 %	0,97 %
All systematics	1,89 %	1,74 %	2,56 %	2,53 %	5,63 %	2,45 %

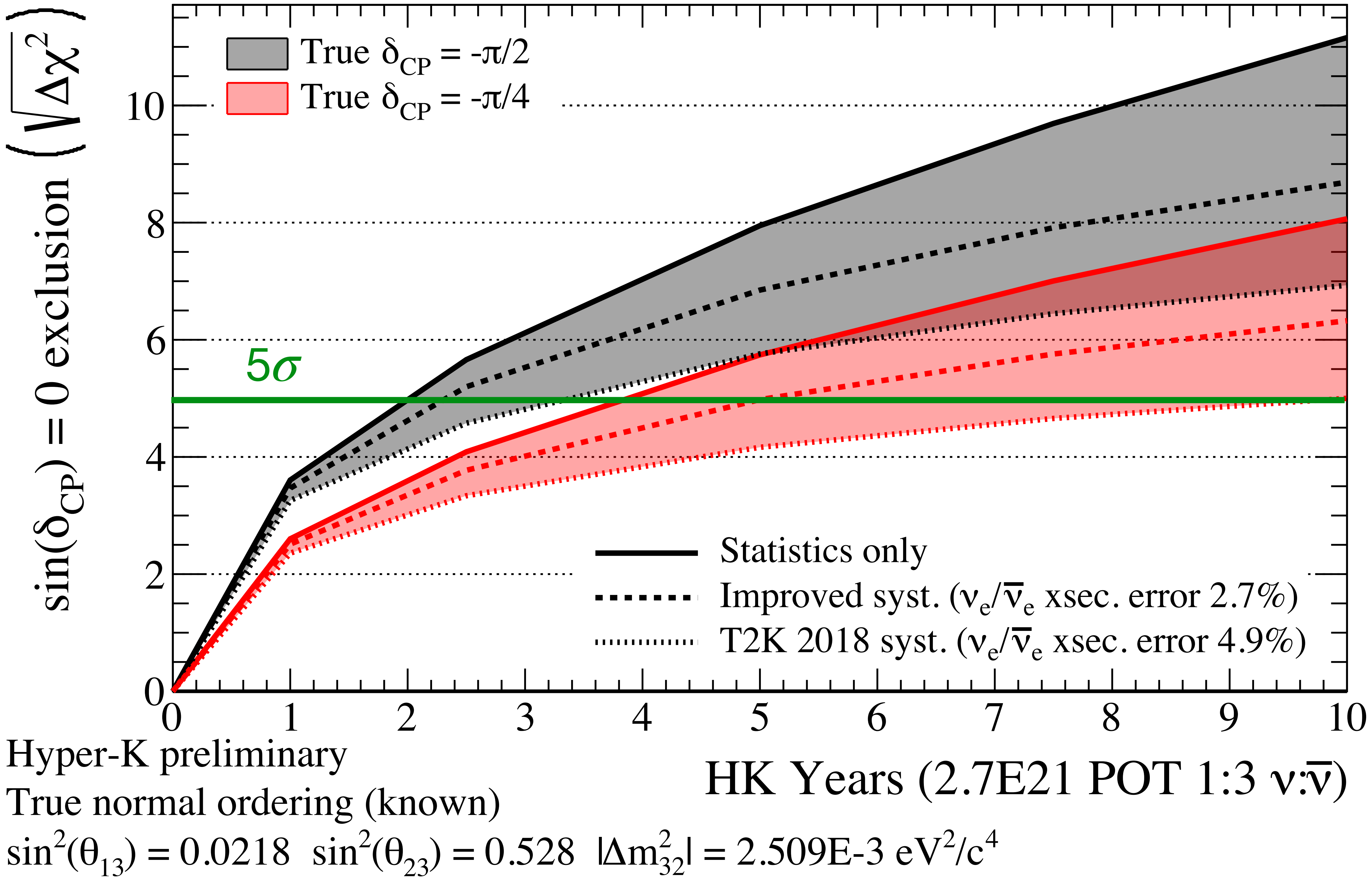
*The improved systematic constraints are obtained from the T2K constraints where we shrink the errors on systematic parameters taking into account:

- The statistics increase
- The expected effects of the upgrades

Systematic uncertainties

Impact on the sensitivity





Systematic uncertainties will impact precision measurements, the potential discovery of CP violation…

Neutrino interactions uncertainties

At 600MeV, the most common neutrino interaction is the **Charged Current Quasi-Elastic.**

But the reality of neutrino interactions is more complex.

Uncertainties on neutrino interactions and cross-sections will impact:
- Expected event rates
- Energy reconstruction
- Model extrapolation from ND to FD

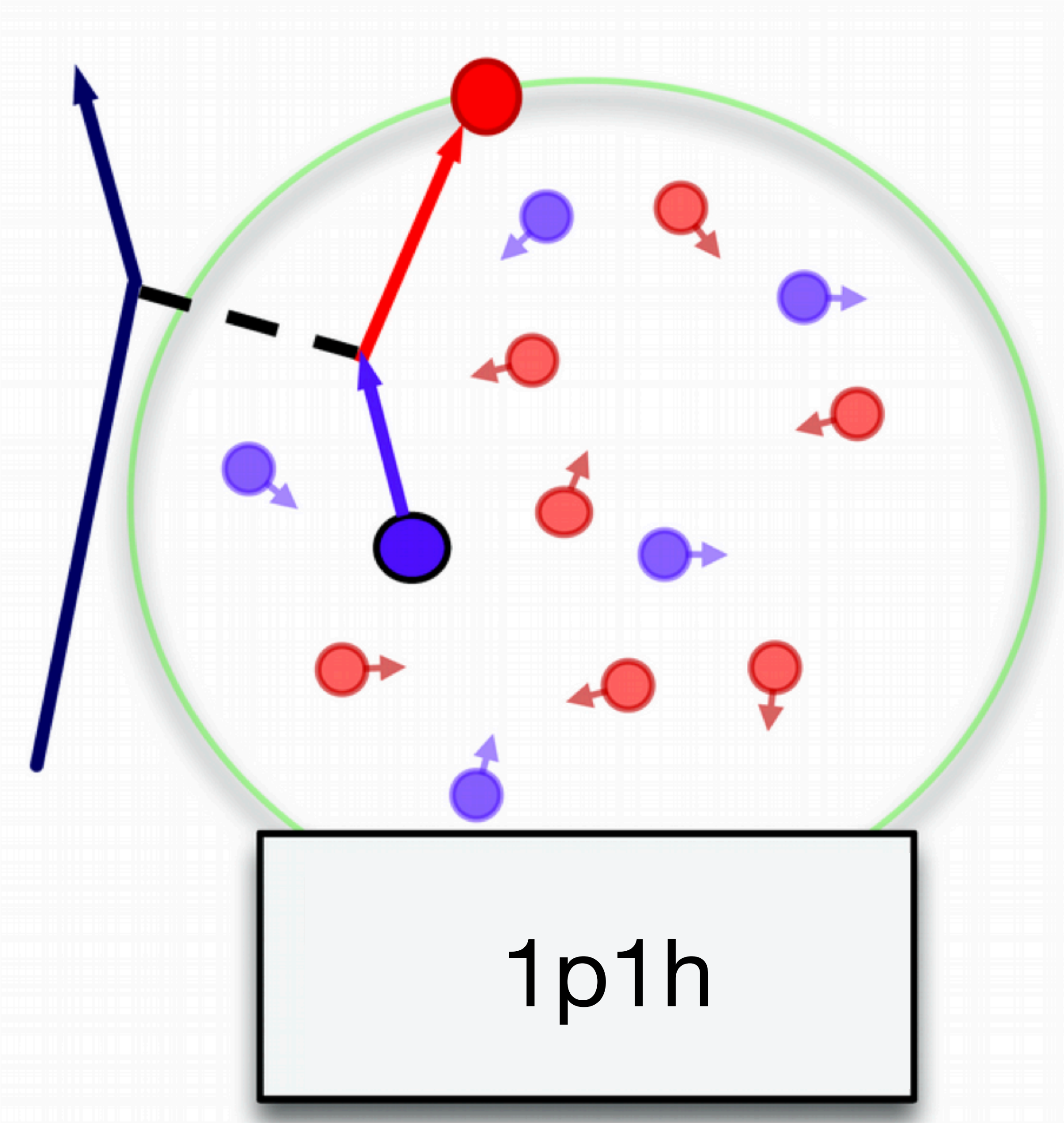
Need a good modelling of those complex interactions!

Take advantage of knowledge acquired with T2K

Neutrino interactions uncertainties

Five main sources of uncertainties considered in HK-LBL*:

1. **1p1h** (CCQE): interaction with a nucleon + 1 nucleon ejected
   Need to take nuclear effects into account
2. 2p2h
3. CC1π
4. Deep Inelastic Scattering
5. Final State Interaction

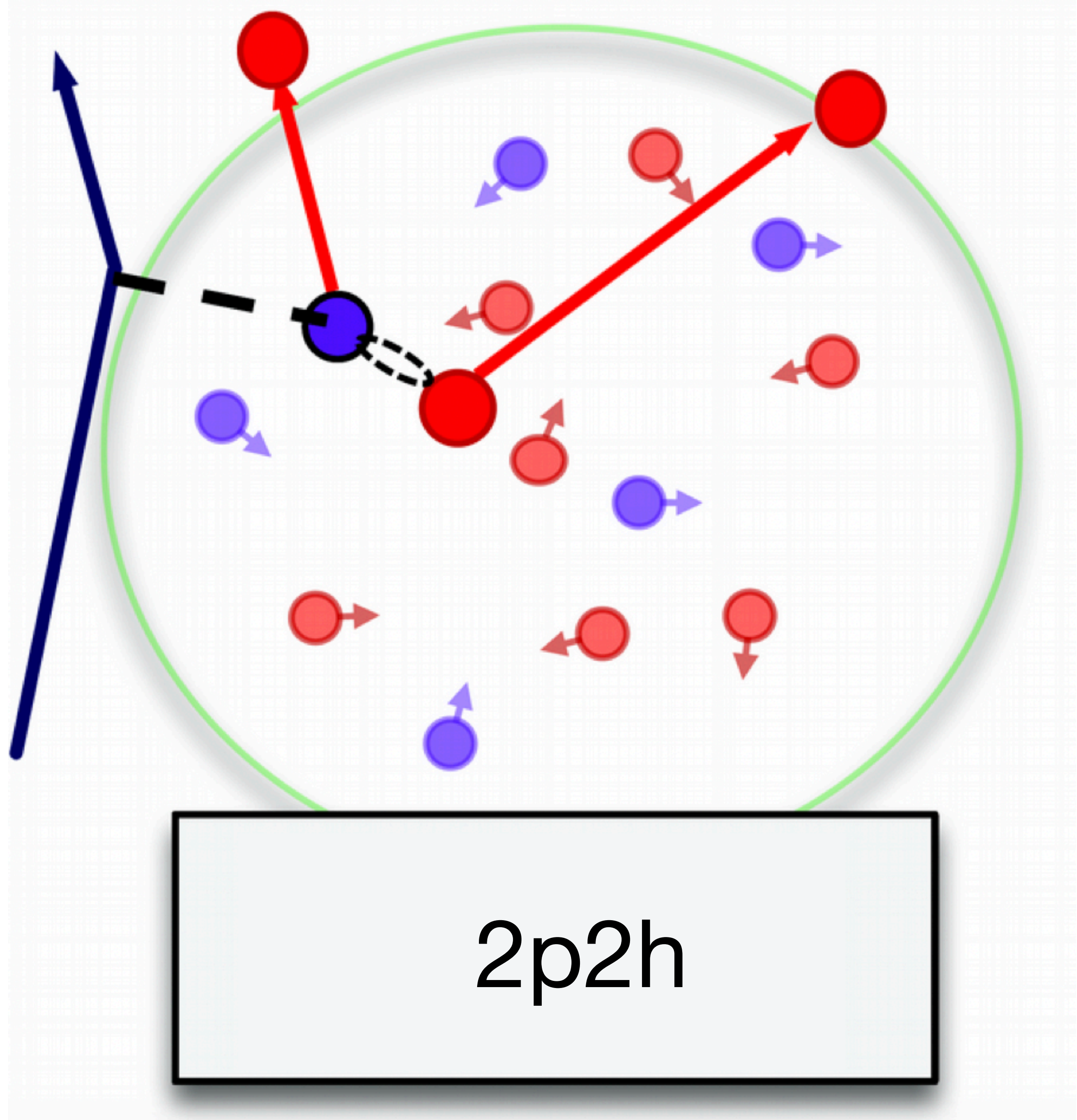


* Based on T2K error model in latest published results (ref. 1)

Neutrino interactions uncertainties

Five main sources of uncertainties considered in HK-LBL*:

1. 1p1h
2. **2p2h**: interaction with two nucleons instead of 1.
3. CC1π
4. Deep Inelastic Scattering
5. Final State Interaction



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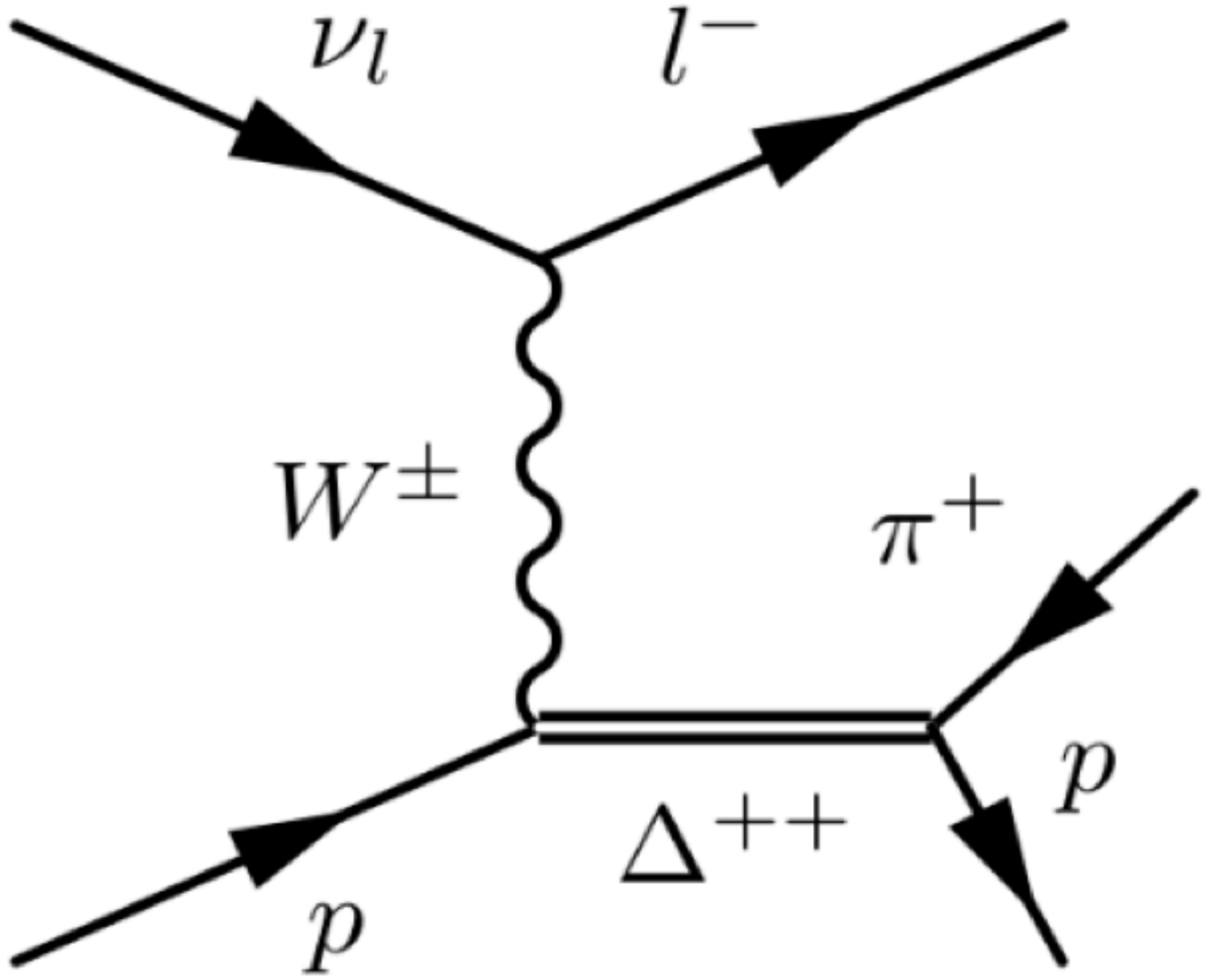
Neutrino interactions uncertainties

Five main sources of uncertainties considered in HK-LBL*:

1. 1p1h
2. 2p2h
3. **CC1π**: a pion is produced by the neutrino interaction
4. Deep Inelastic Scattering
5. Final State Interaction

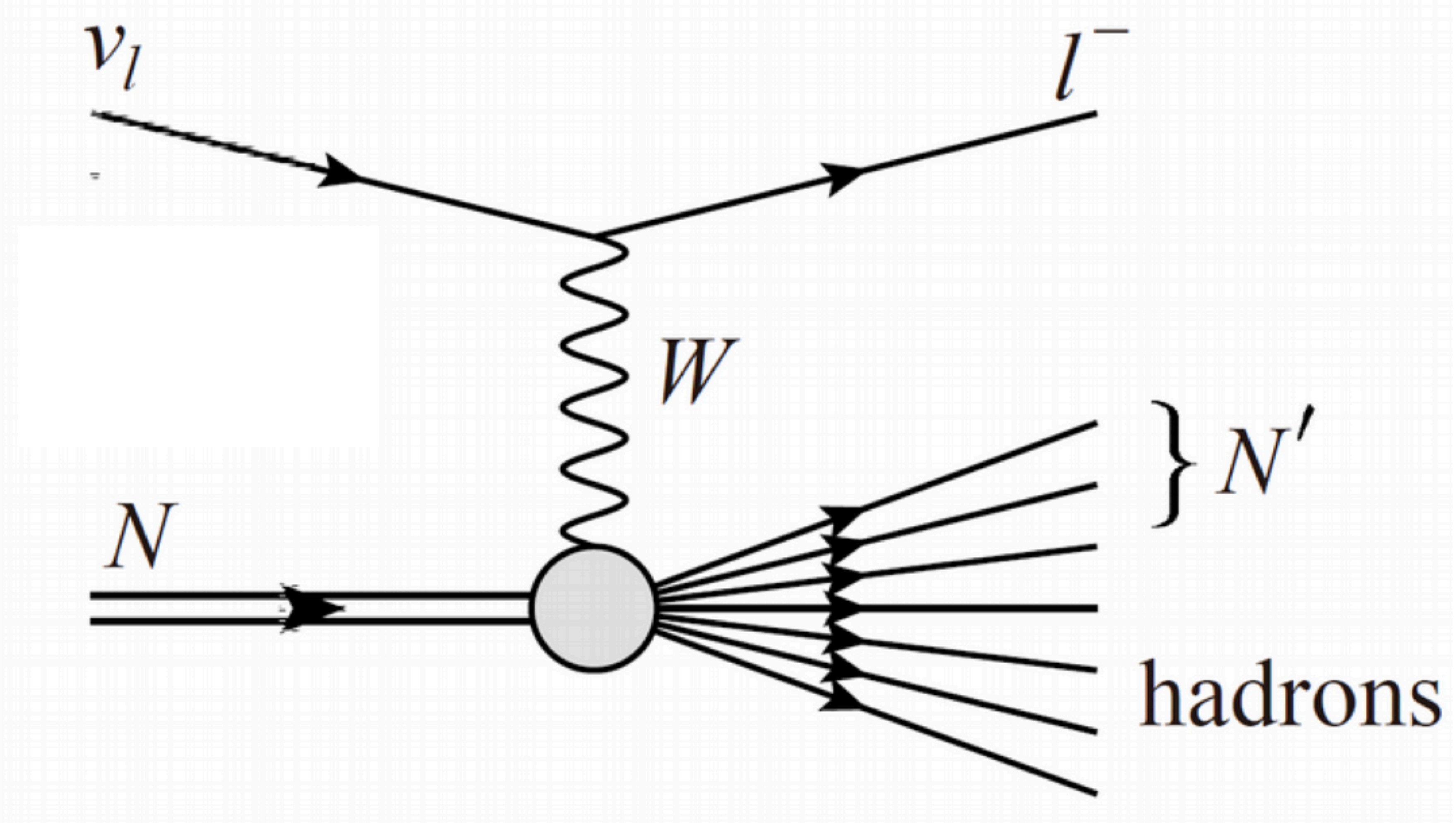


Example of CC1π via a Δ^{++} resonance

* Based on T2K error model in latest published results (ref. 1)

Neutrino interactions uncertainties

Five main sources of uncertainties considered in HK-LBL*:



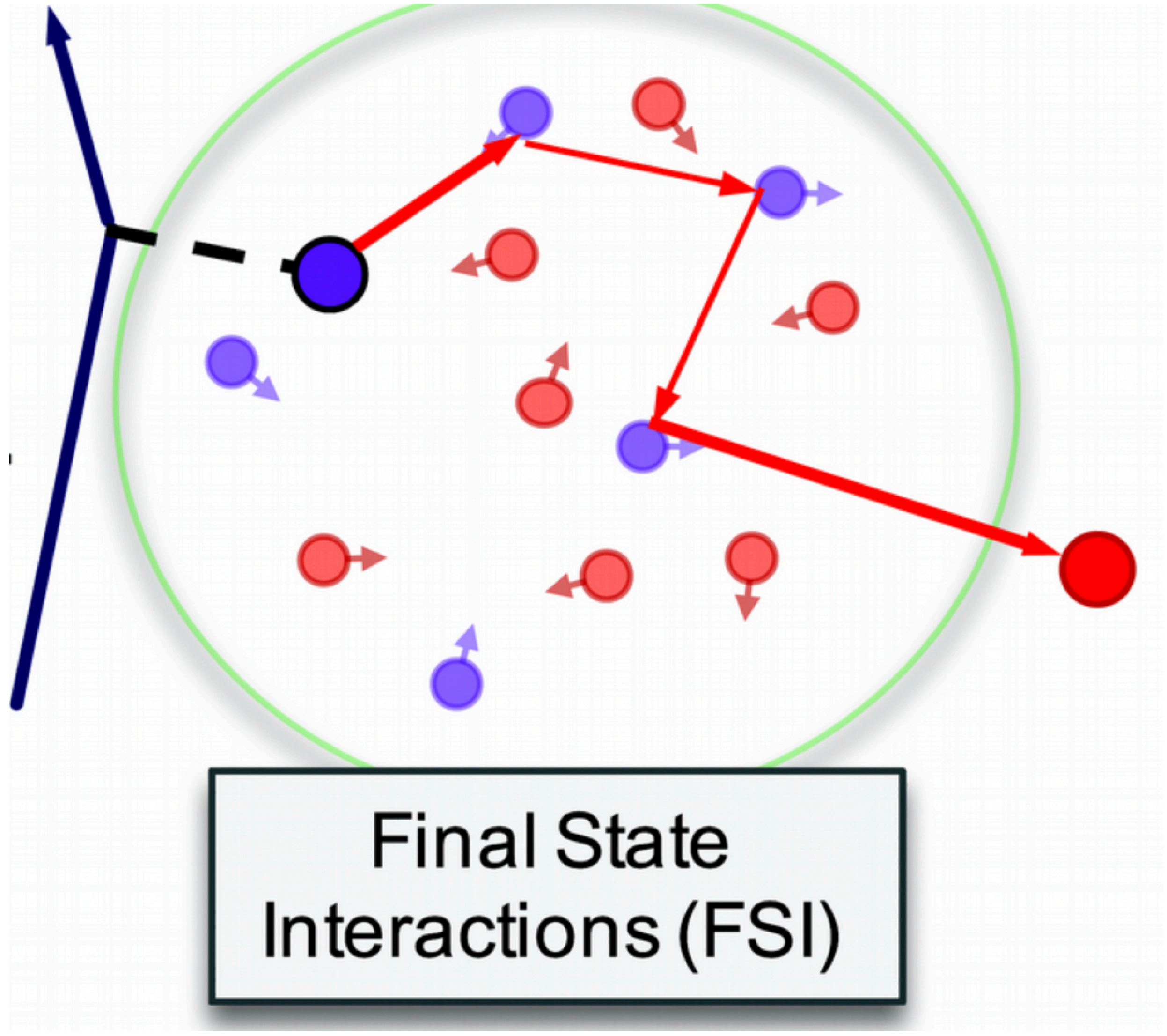
1. 1p1h
2. 2p2h
3. CC1π
4. **Deep Inelastic Scattering**: very complicated final state
5. Final State Interaction

* Based on T2K error model in latest published results (ref. 1)

Neutrino interactions uncertainties

Five main sources of uncertainties considered in HK-LBL*:

1. 1p1h
2. 2p2h
3. CC1π
4. Deep Inelastic Scattering
5. **Final State Interaction**: final state changed by interactions of produced particles in the nuclear medium



* Based on T2K error model in latest published results (ref. 1)

Plan to reduce systematics

- **Good modelling** of neutrino interaction necessary to **optimise the parametrisation of uncertainties** in LBL experiments.

- **T2K regularly updates** this parametrisation: this **knowledge** will be very important for **HK**.

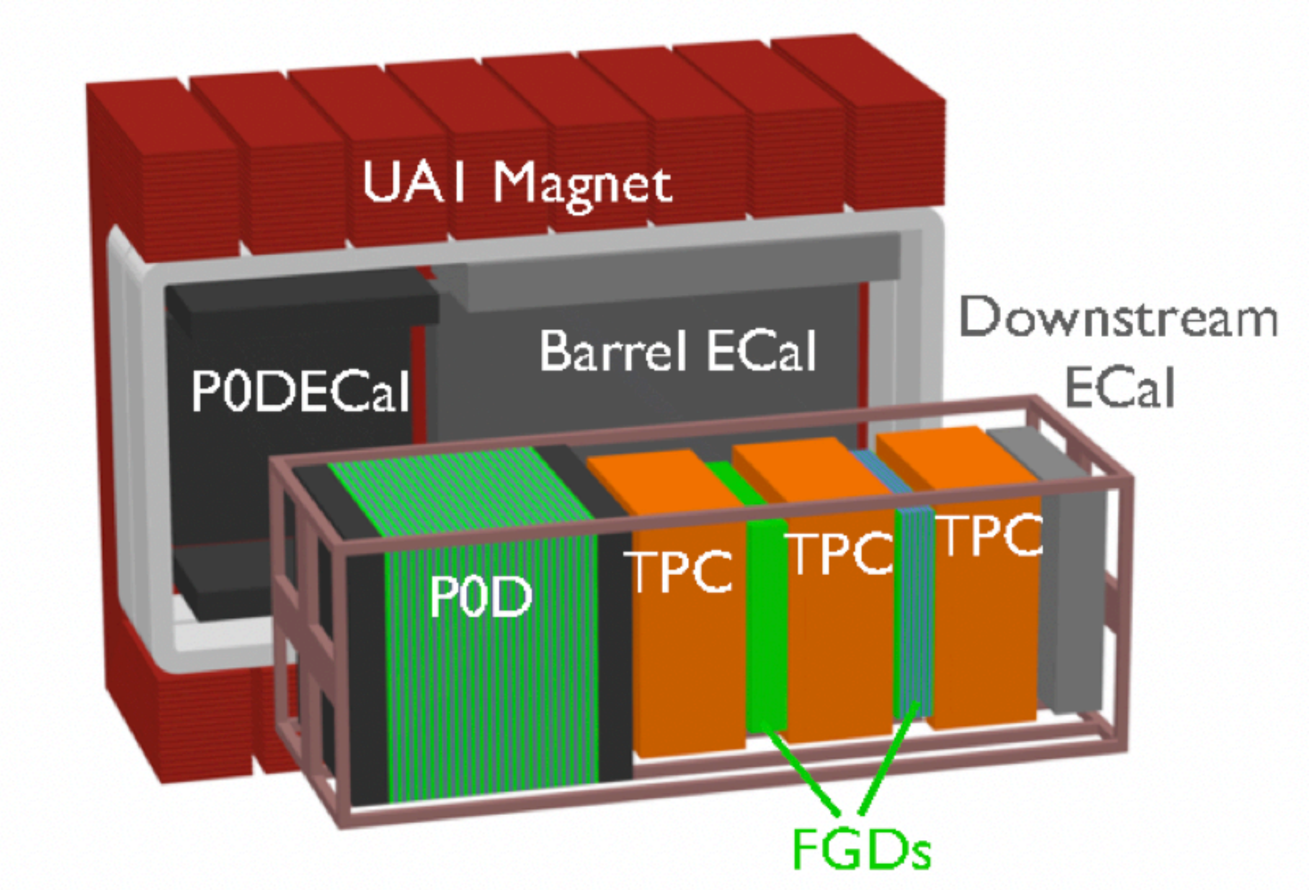
- Most **cross-section systematics constrained**, with the flux systematics, thanks to the **near detectors**. Some **upgrades** of T2K ND will be implemented to more efficiently constrain systematics.

Plan to reduce systematics

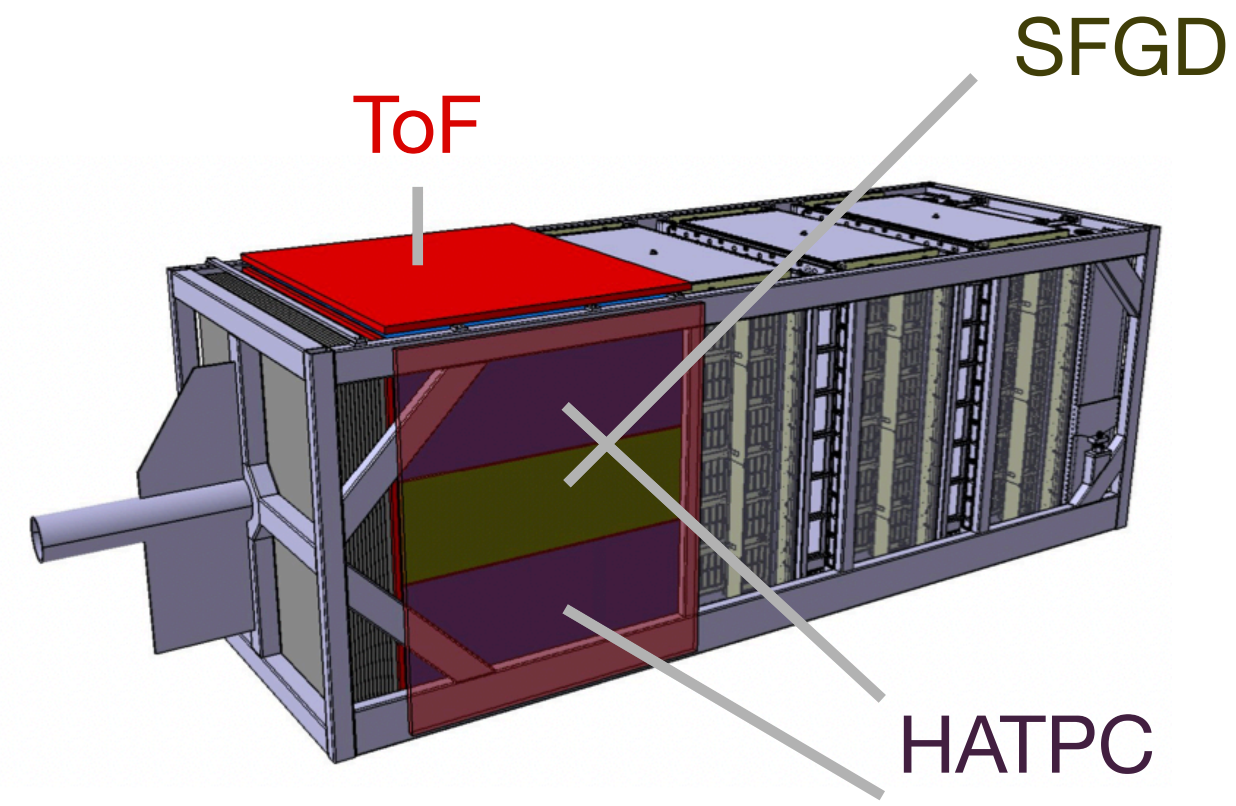
ND280 upgrade(s)

For T2K-II, ND280 already being upgraded*. **P0D** detector replaced by:

- A **Super-Fine-Grained Detector** (2.1 million 1cm^{3}scintillating cubes): higher reconstruction efficiency at high scattering angles
- Two **High Angle TPCS** (below and above SFGD)
- 6 **Time of Flight** panels: to measure direction of particles



Old ND280



ND280 after current upgrade:
Fiducial mass multiplied by 2
+ better angular coverage

R&D is ongoing for the upgrade of the second half of ND280 for HK

→**ND280 upgrade ++**

Example: TPCs replaced by a **10 tons SFGD, final fiducial mass multiplied by 5** compared to old ND280

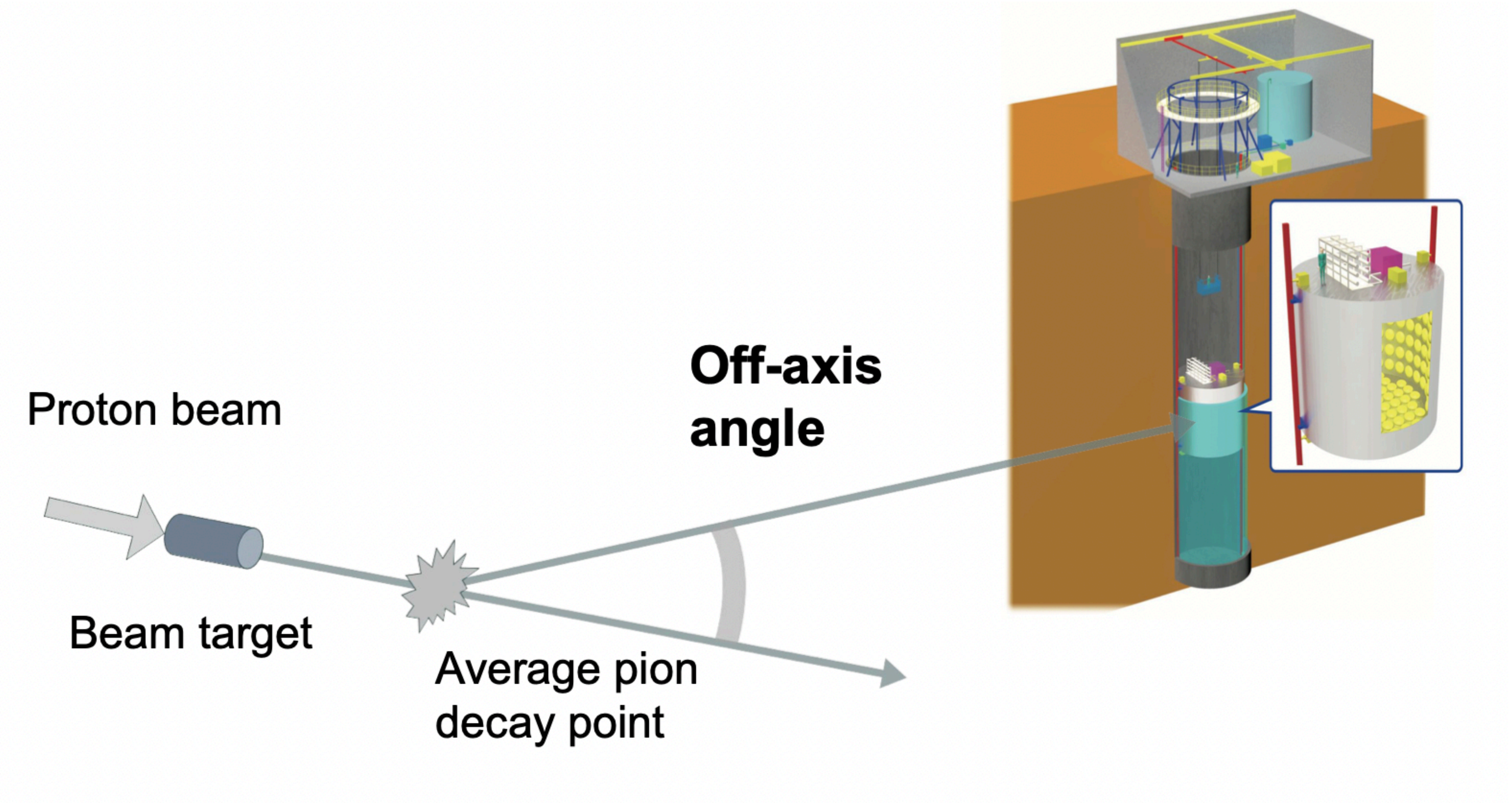
* See ref. 2 and Xingyo Zhao's talk on ND280 upgrade for more details

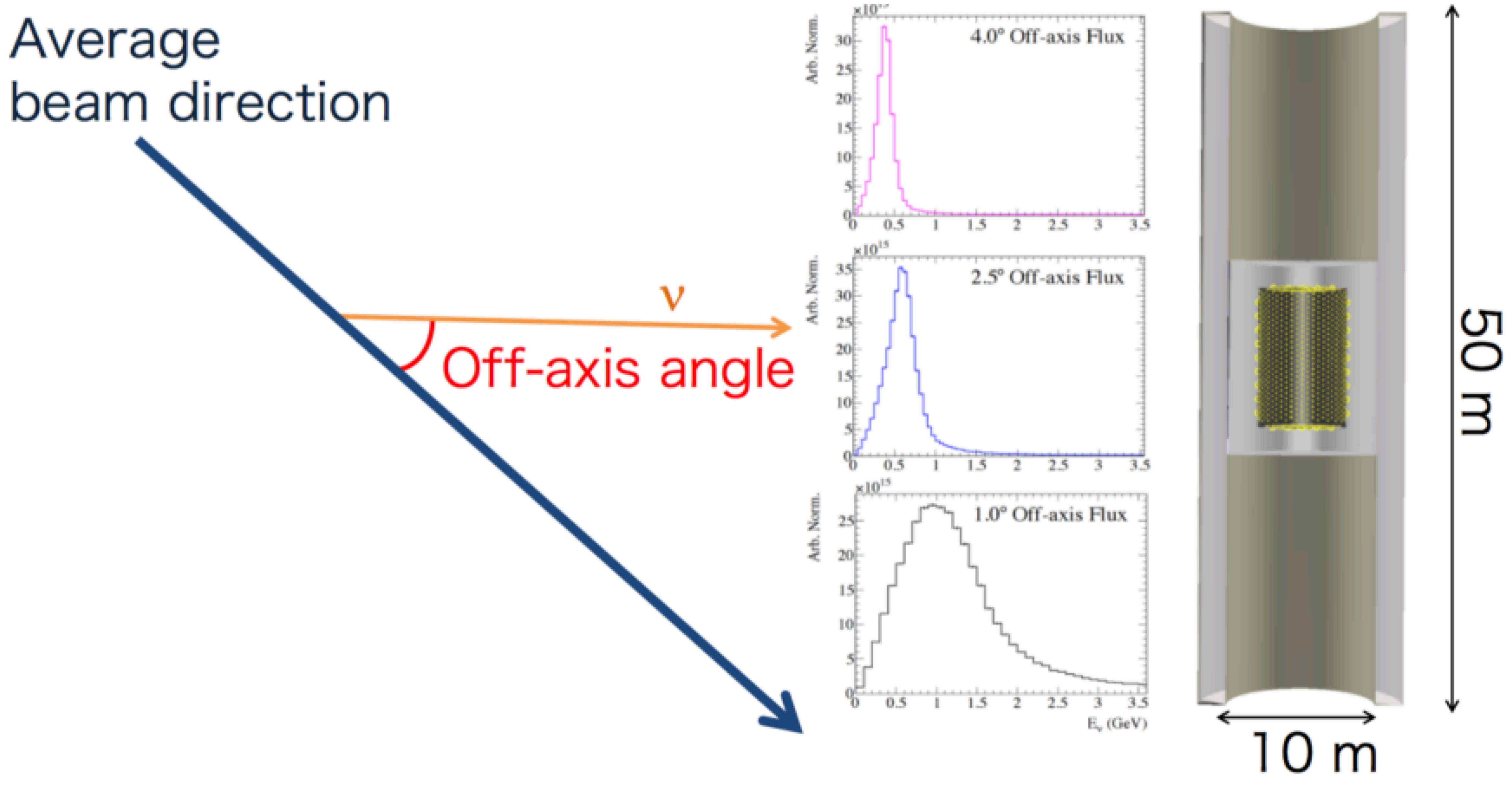
Plan to reduce systematics

IWCD

Plan to build a **vertically movable water Cherenkov** detector at ~1km from target. Would present a lot of advantages to reduce neutrino interaction uncertainties:

- Same target material as FD
- Vertically movable = varying off-axis angle: allows to scan different flux configurations and increase statistics at higher neutrino energies (constrain non QE interactions)





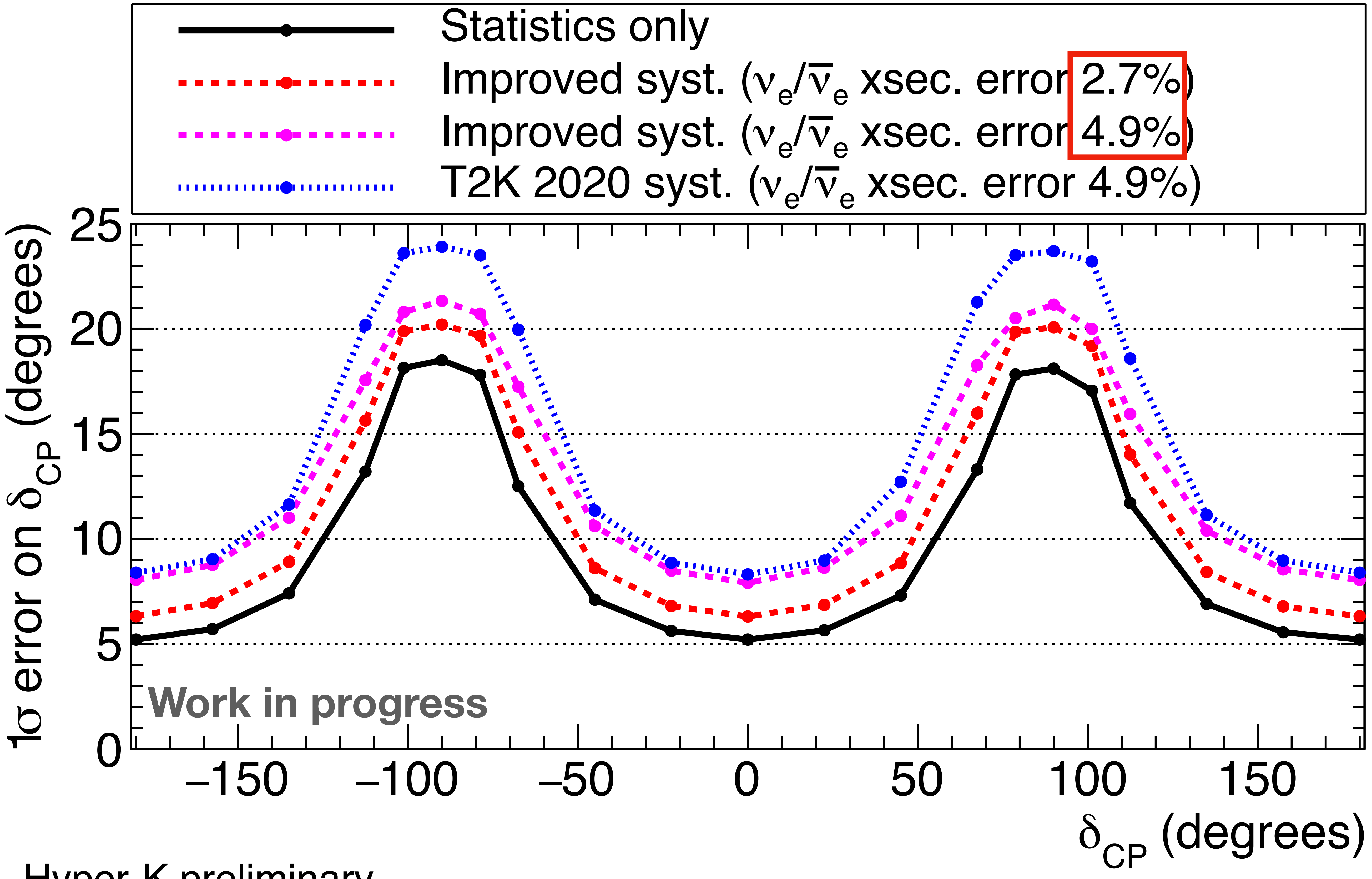
Credit: Evangelia Drakopoulou, POS 2017

Plan to reduce systematics

Hyper-Kamiokande

Example: $\nu_e/\bar{\nu}_e$ cross-section ratio uncertainty

- **$\nu_e/\bar{\nu}_e$ cross-section ratio** uncertainty measurement **challenging** due to **very low statistics**
- In **T2K**, ND280 $\nu_e(\bar{\nu}_e)$ selection not pure/efficient enough to constrain this systematic: use **theoretical constraint of 4.9%**.
- For **HK, experimentally constrain** $\nu_e/\bar{\nu}_e$ cross-section ratio with ND280 upgrade (++) and IWCD



Hyper-K preliminary

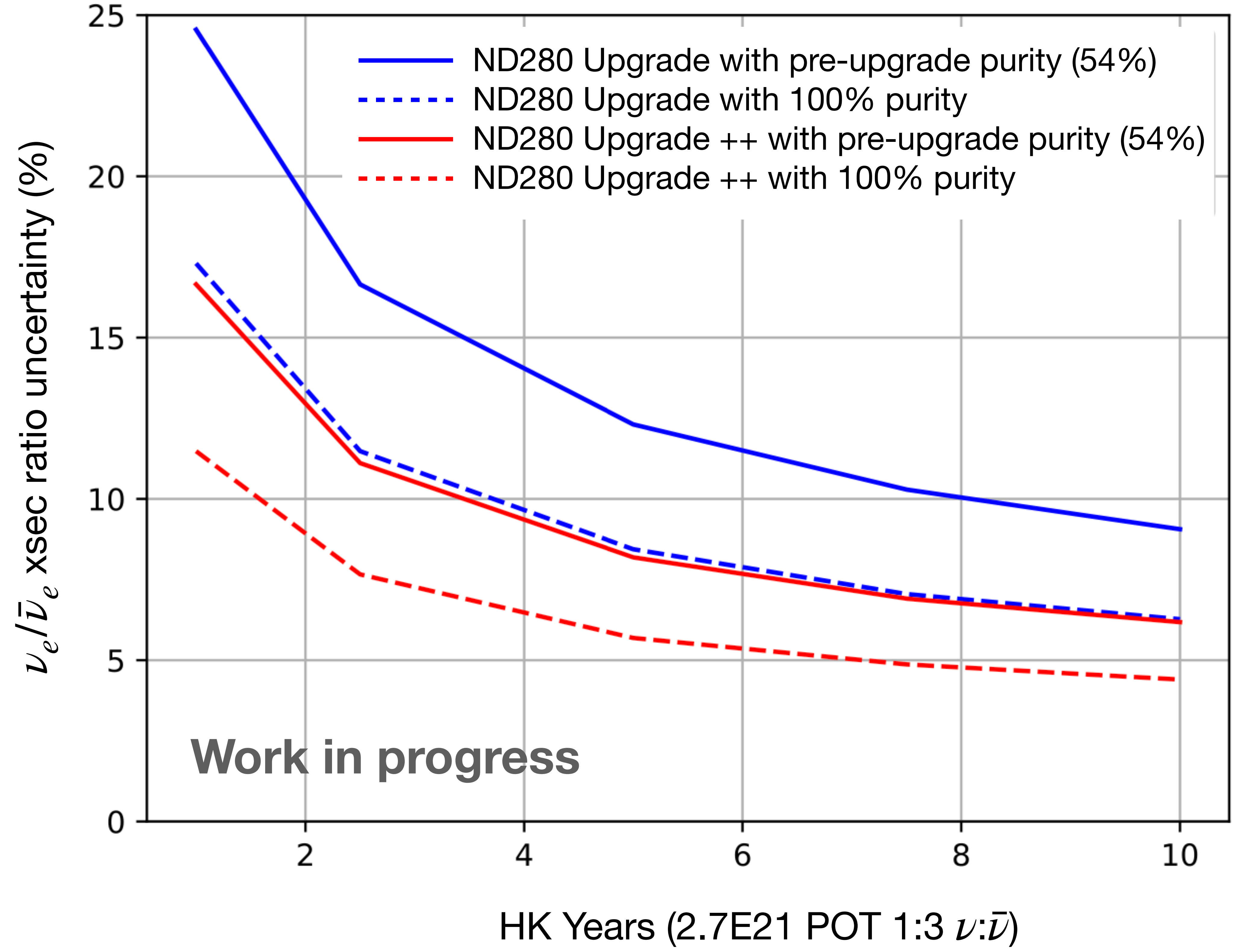
True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 $\nu:\bar{\nu}$)

$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$

Plan to reduce systematics

Example: $\nu_e/\bar{\nu}_e$ cross-section ratio uncertainty

Estimation of ND280 constraint on $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ with upgrade or upgrade ++ mass, pre-upgrade efficiency and pre-upgrade or 100% purity.



With **only ND280 upgrade**, could reach a **~7.5%** uncertainty or below with the upgrade ++

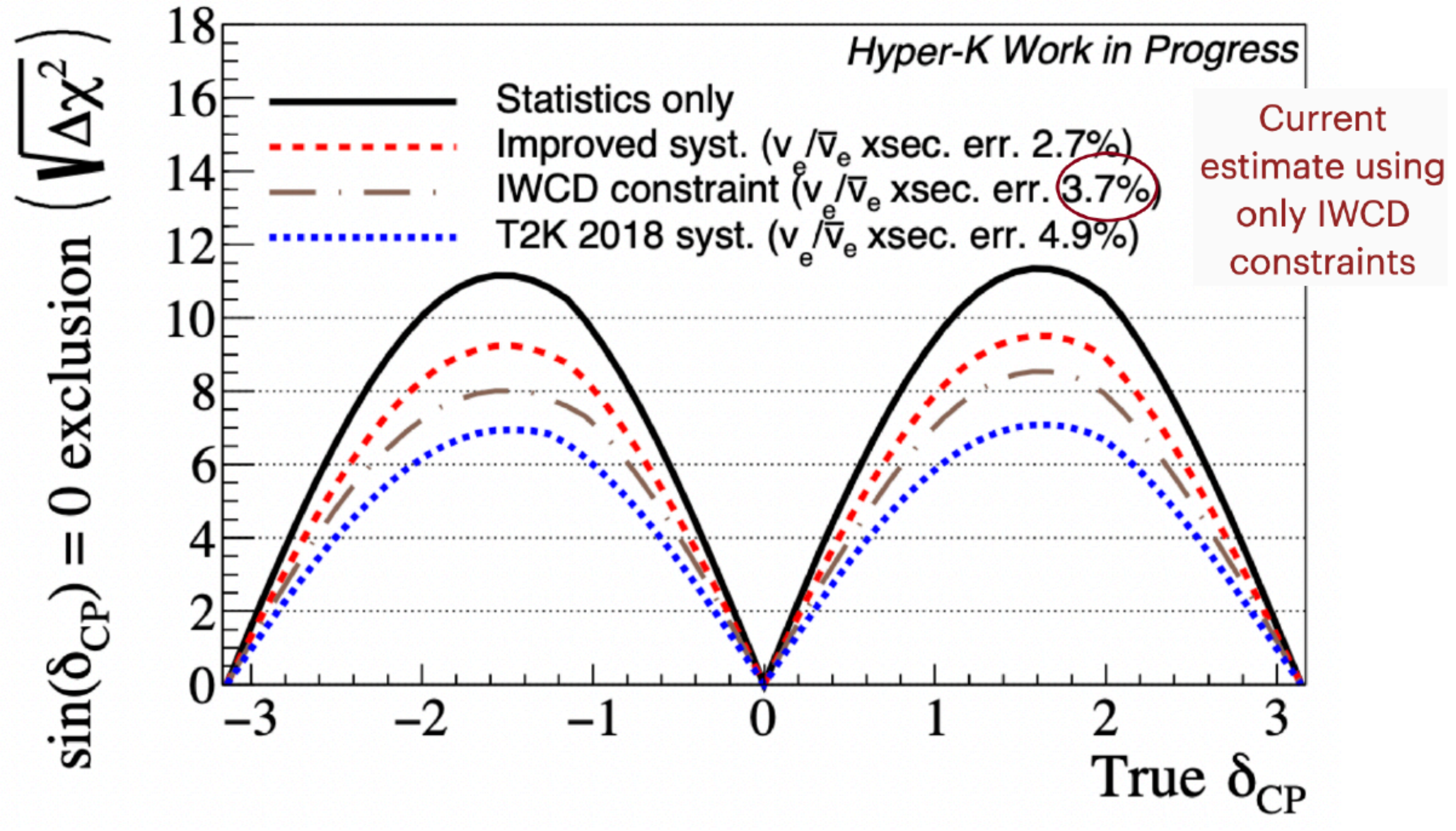
Claire Dalmazzone, NNN23, Procida (Italy)

Plan to reduce systematics

Example: $\nu_e/\bar{\nu}_e$ cross-section ratio uncertainty

With **only IWCD**, could reach a **$\sim$3.7%** uncertainty

With **ND280 upgrade (++) and IWCD**, the goal is to go **below 3%** uncertainty after 10 years of HK-LBL



Current estimate using only IWCD constraints

Significance level to exclude the CP-conserving values (0 and $\pm\pi$) of δ_{CP} after 10 years with HK.

* See ref. 4 for more details

Conclusion

Hyper-Kamiokande

- **Hyper-Kamiokande** is a **next generation water Cherenkov** neutrino detector with a **vast physics program.** Construction on-going, start **data-taking in 2027**
- The **long baseline program** will benefit from the **knowledge acquired with T2K** and a much **faster accumulation of statistics** to measure challenging quantities like δ_{CP}
- The oscillation parameters measurements will eventually be limited by **systematic effects** and **neutrino interactions** are a major source of systematic uncertainties.
- Reducing these uncertainties will be possible thanks to a **good modelling of the neutrino interactions** in HK and to the **improved and new near detectors**: ND280 and IWCD.

Thank you!

References

1. The T2K Collaboration, *Measurements of neutrino oscillation parameters from the T2K experiment using* 3.6×10^{21} *protons on target*, 2023, arXiv:2303.03222
2. Thorsten Lux (T2K), *The upgrade of the T2K ND280 detector*, Journal of Physics: Conference Series, 2374(1):012036, nov 2022
3. Ferrero A. (T2K), *The ND280 Near Detector of the T2K experiment*, AIP Conf. Proc., 1189, 77-82, 2009
4. Tailin Zhu (Hyper-Kamiokande), *Long-baseline neutrino oscillation sensitivities with Hyper-Kamiokande and impact of Intermediate Water Cherenkov Detector*, In Proceeding of Neutrino Oscillation Workshop: PoS(NOW2022), volume 421, page 028, 2023

Back-up

Systematic uncertainties

HK Improved systematics error model

The **HK Improved error model** is built from the **T2K** one by **shrinking the uncertainties** on each systematic parameter to take into account the **increased statistics** and the **ND upgrades**:

1. **Errors divided by sqrt of beam exposure increase** compared between T2K and HK at 10 years
2. Further **factor 2-3 reduction for come cross-section** parameters based on studies made on **ND280 upgrade and IWCD** sensitivity
3. Error on $\nu_e/\bar{\nu}_e$ **cross-section ratio** fixed to **2.7%** (**HK goal** motivated by studies on **IWCD sensitivity**)

Neutrino interactions uncertainties

Interactions not constrained at ND

Other cross-section uncertainties are currently not constrained with ND280 data in T2K oscillation analysis:

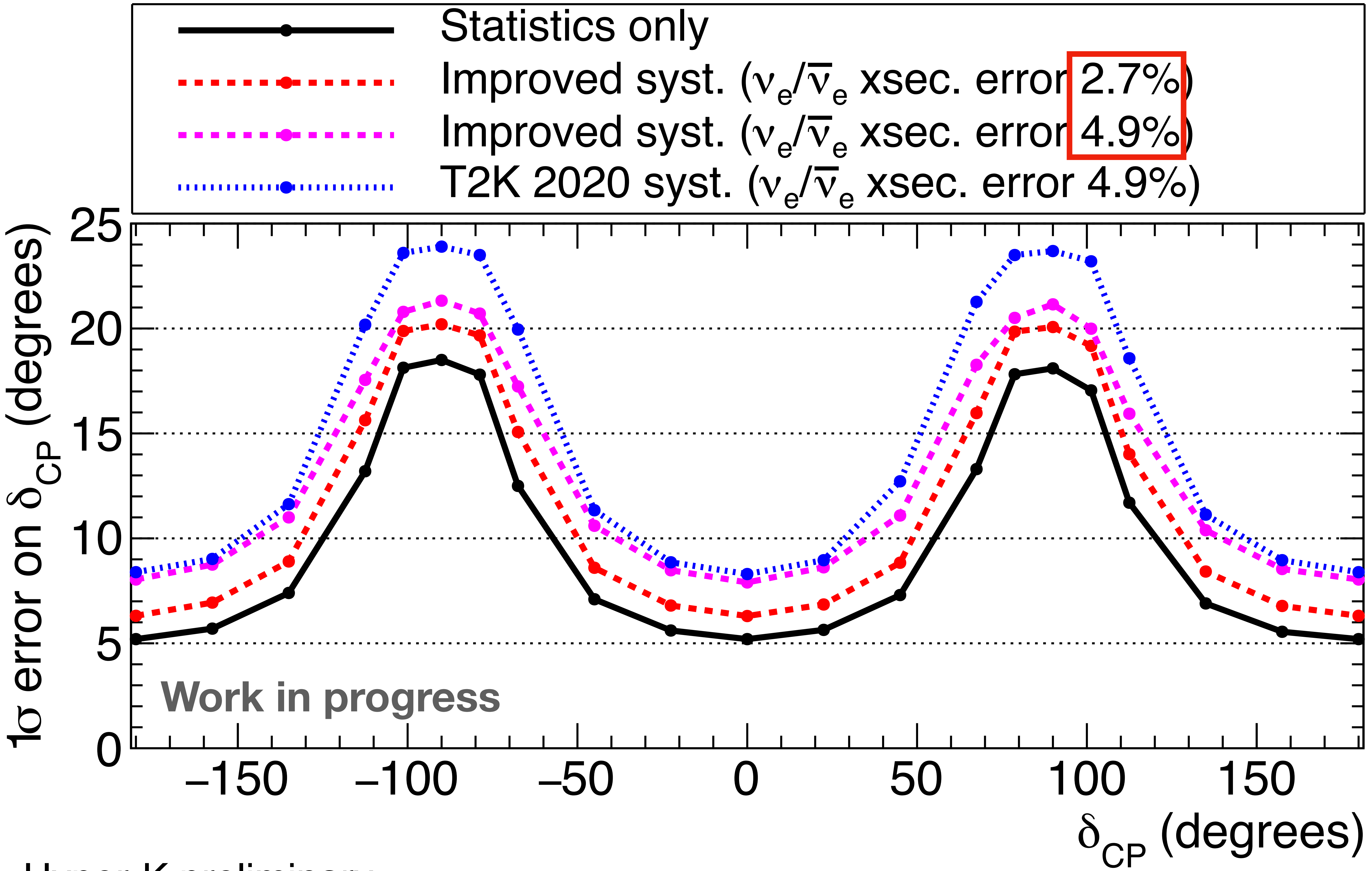
- NCγ: NC interaction producing a photon. Background for e-like samples in ND280.
- Background coming from CC interactions of antineutrinos with low momentum pion production that is thus missed.
- Shape of the energy dependence of 2p2h interactions.

Plan to reduce systematics

Hyper-Kamiokande

Example: $\nu_e/\bar{\nu}_e$ cross-section ratio uncertainty

- $P_{osc}(\delta_{CP}) = f\cos\delta_{CP} + g\sin\delta_{CP} + h$
- $\nu_e/\bar{\nu}_e$ xsec error mostly limits the resolution of CP-odd term
- Gradient of CP-odd (-even) term is maximum at $\sin\delta_{CP} = 0(\pm 1)$
- $\nu_e/\bar{\nu}_e$ xsec error expected to impact δ_{CP} resolution mostly at $\sin\delta_{CP} = 0$



Hyper-K preliminary

True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)

$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\,\mathrm{eV}^2/c^4$

Octant degeneracy