TOSHIKO YUASA LABORATORY
FRANCE-JAPAN PARTICLE PHYSICS

FJPPN NU-09 project

Characterisation of the upgraded J-PARC neutrino beam for the T2K-II and HK experiments

T2K

Hyper-Kamiokande

Claire Dalmazzone, 14-16 May 2025, Nantes, France

SORBONNE UNIVERSITÉ

LPNHE PARIS

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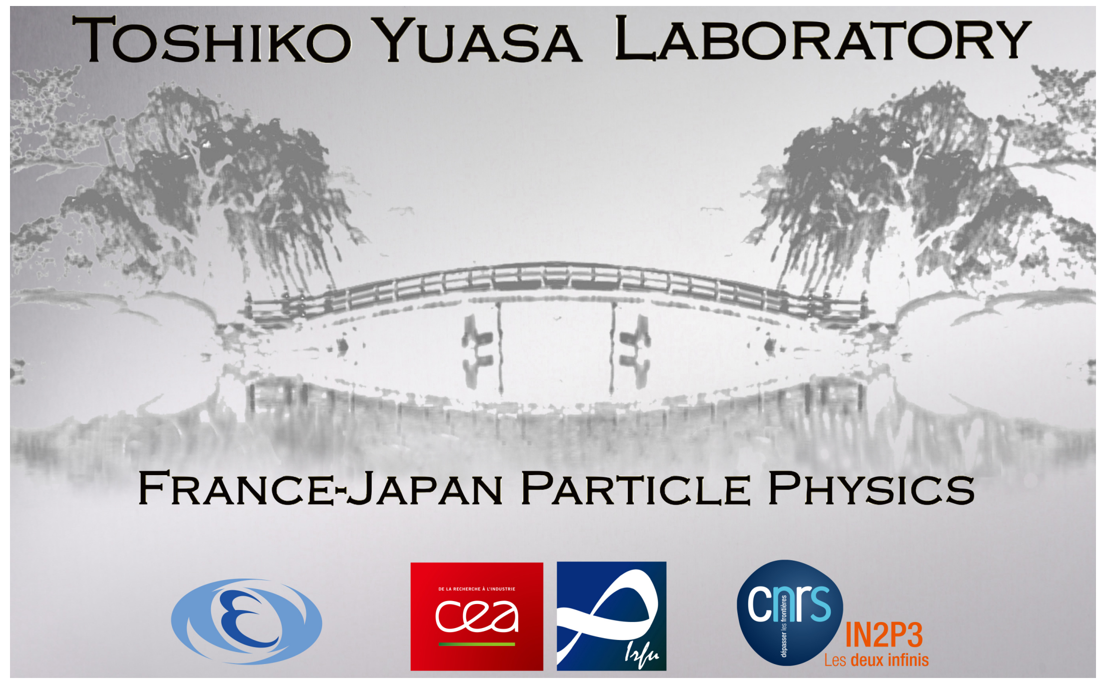

NU-09 project

NU-09 project

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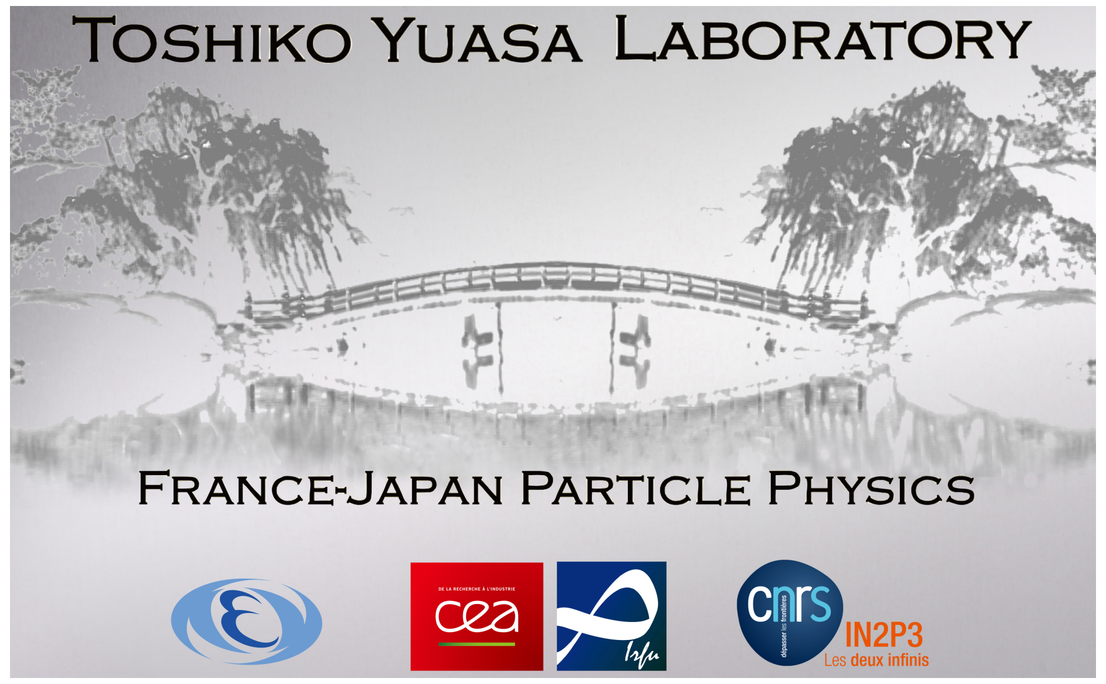


NU-09 project

Goals

Members of the France-Japan collaboration are all involved in the current **T2K** and future **Hyper-Kamiokande (HK)** experiments.

The goals are:

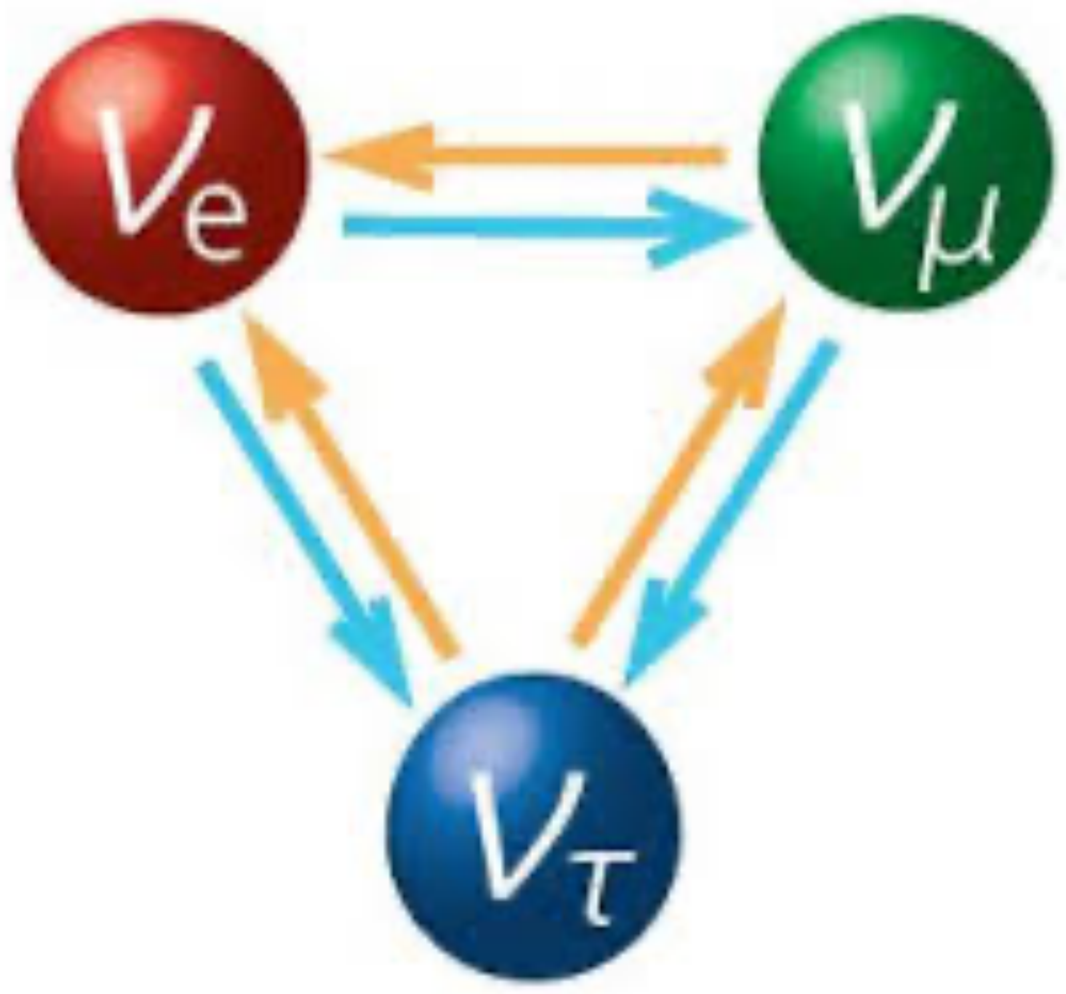
- **Improve the knowledge** of the upgraded **(anti)neutrino beam** produced at J-PARC for T2K-II and HK
- Analyse the data of hadron production in **T2K replica target collected by NA61/SHINE** experiment in 2022 in order to **improve the knowledge of the (anti)neutrino flux** in T2K (and later HK)
- Develop the system to **synchronise the near and far detectors of HK**

Neutrino flavour oscillation

Neutrino flavour oscillation

Flavour oscillation: quantum effect due to the **mixing between the flavour states and the mass states**. Its existence means that neutrinos have **non zero mass**.

Oscillation probability depends on: **mixing matrix**, neutrino energy, propagation length, **neutrinos squared mass differences** (Δm^2_{ij})



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

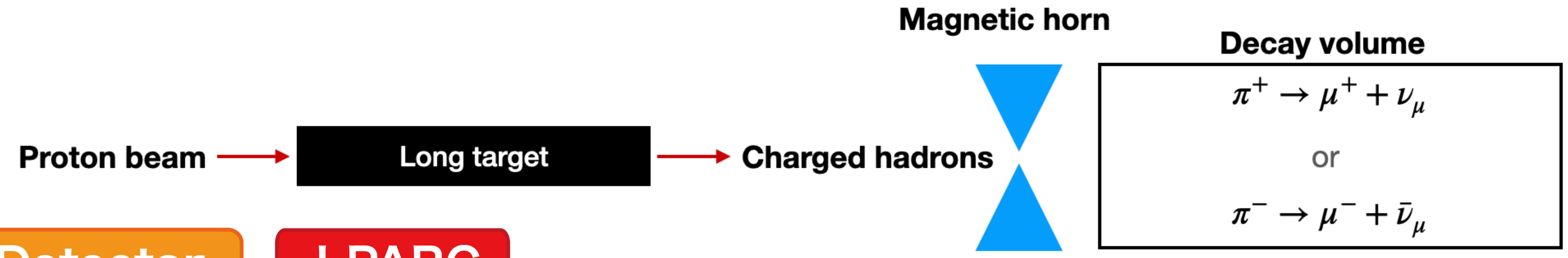
PMNS* parametrisation of the mixing matrix: the three mixing angles (θ_{ij}) and the complex phase δ_{CP} are not predicted and **must be measured experimentally**.

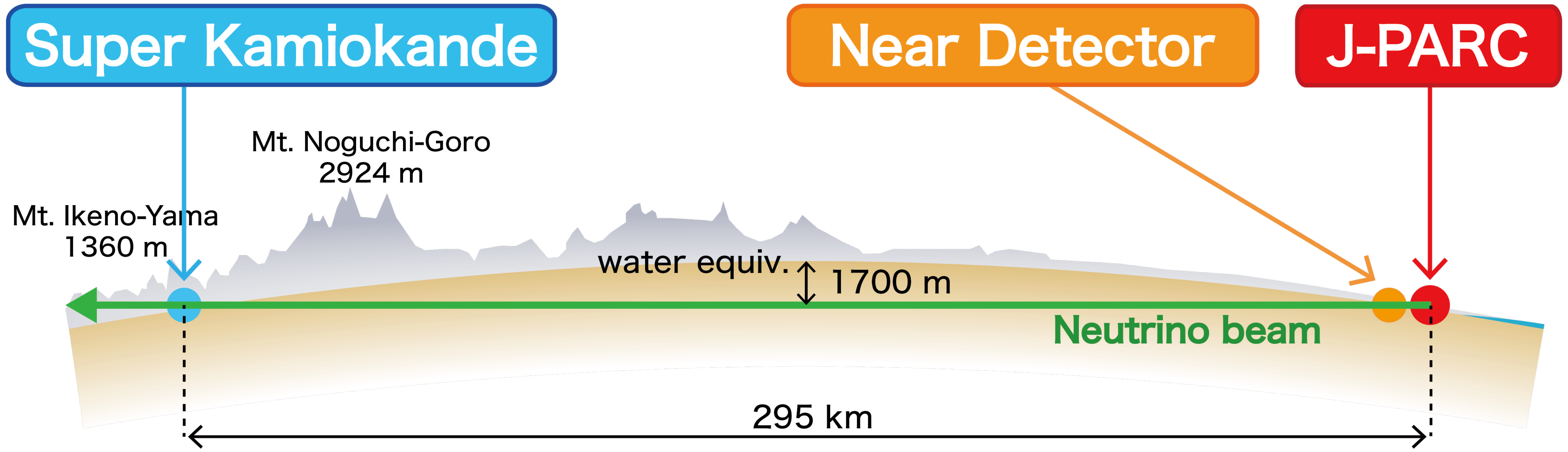
If $\sin\delta_{CP} \neq 0$, neutrinos and anti-neutrinos don't have the same oscillation probability: neutrino oscillation violates CP

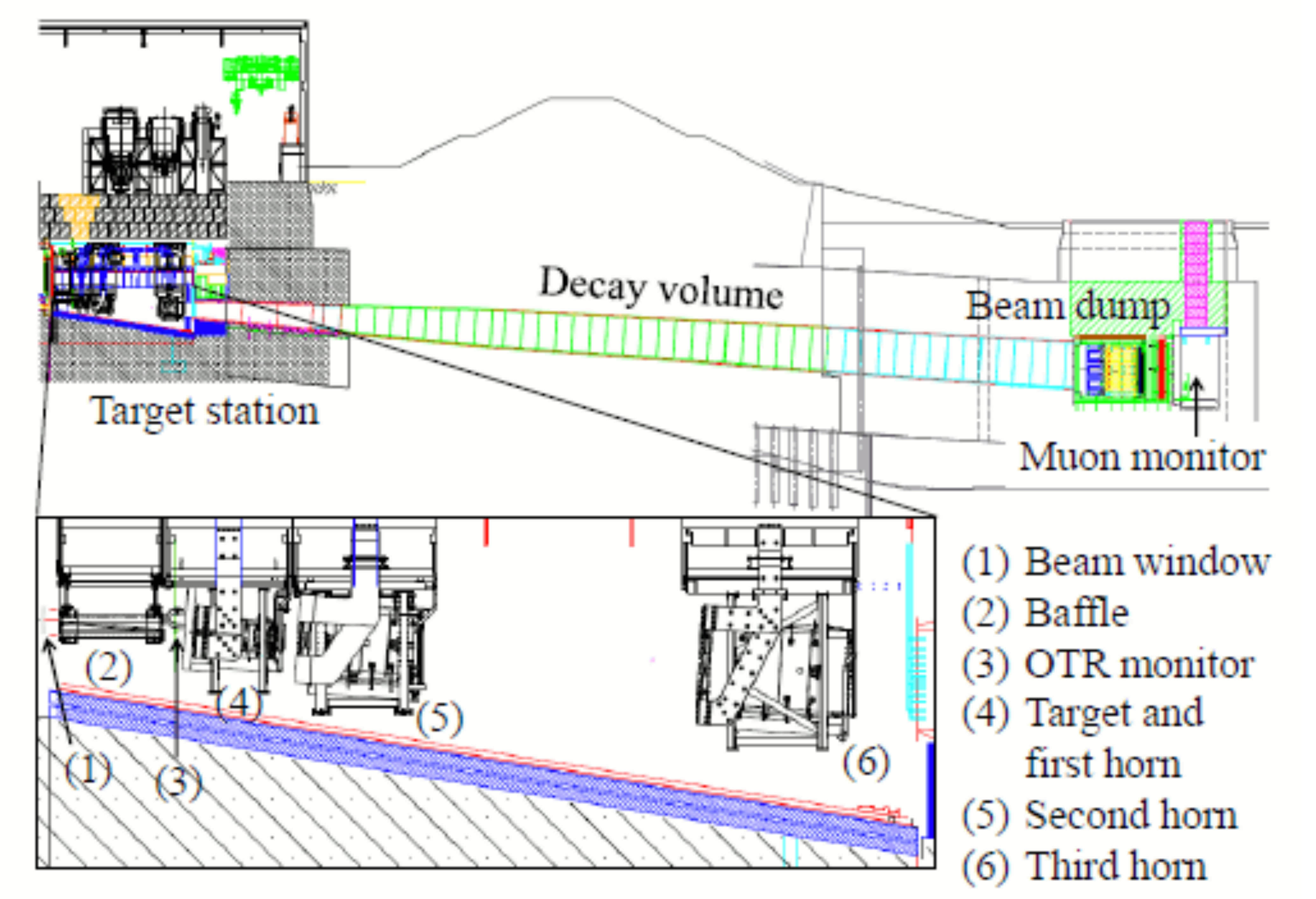
* PMNS for Pontecorvo-Maki-Nakagawa-Sakata

T2K and Hyper-Kamiokande

T2K experiment







Long baseline neutrino oscillation experiments measure the neutrino flavour oscillation to:

- **Precisely measure** neutrino oscillation parameters
- Potentially **discover CP violation** in neutrino oscillation

The J-PARC beamline upgrade will allow a much faster accumulation of statistics for T2K-II and HK.

PhD work

Hyper-Kamiokande experiment

Start of operation in 2027!

Applications:

- Rare nucleon decays
- Neutrino flavour oscillation measurements:
  - Atmospheric neutrinos
  - **J-PARC Accelerator beam neutrinos**
  - MSW effect with solar neutrinos
- Astrophysics:
  - Diffuse Supernova Neutrino Background
  - Solar neutrinos
  - Multi-messenger astrophysics (e.g.: Supernovae)

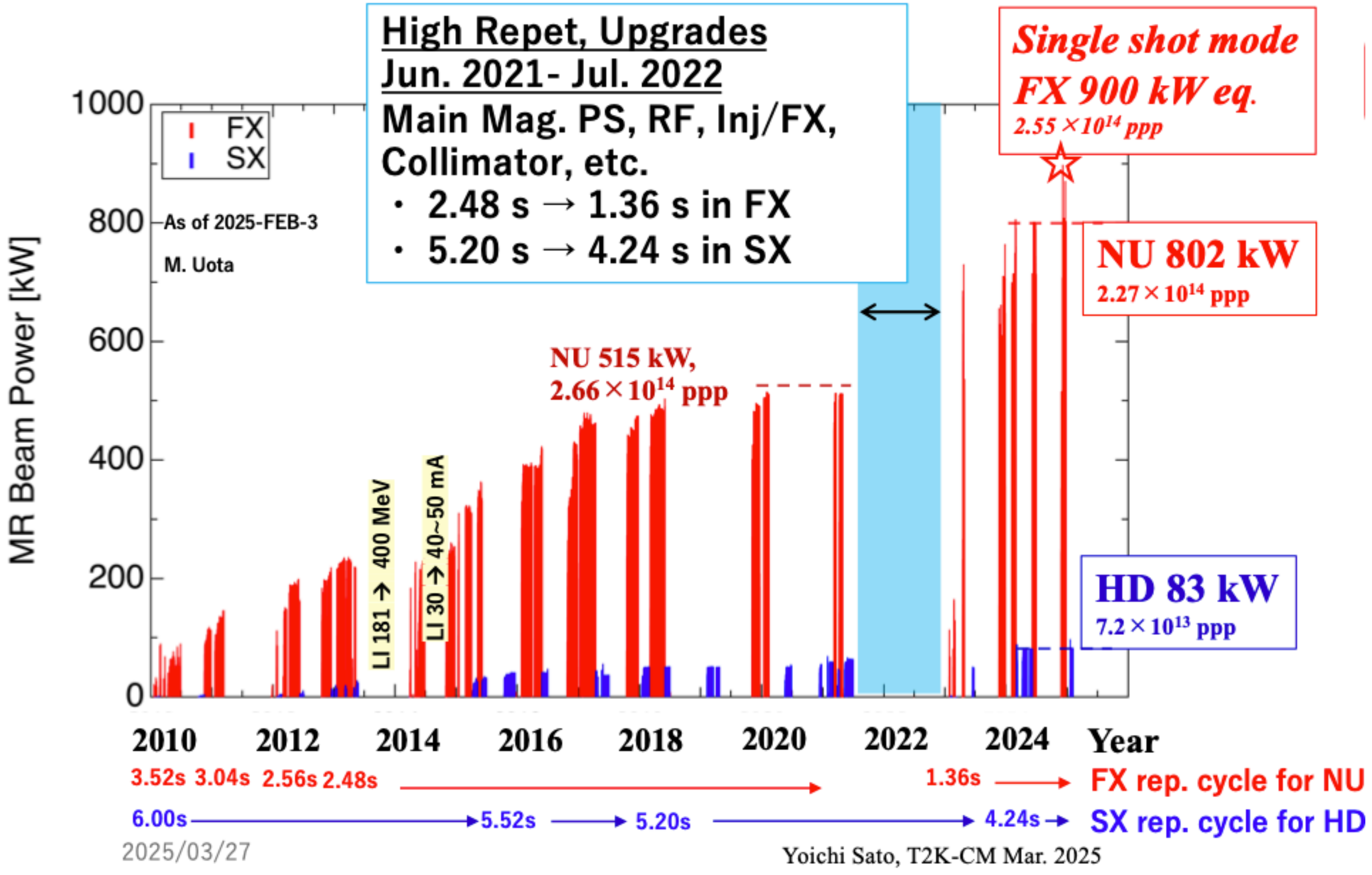
T2K beam operation

T2K beam operation

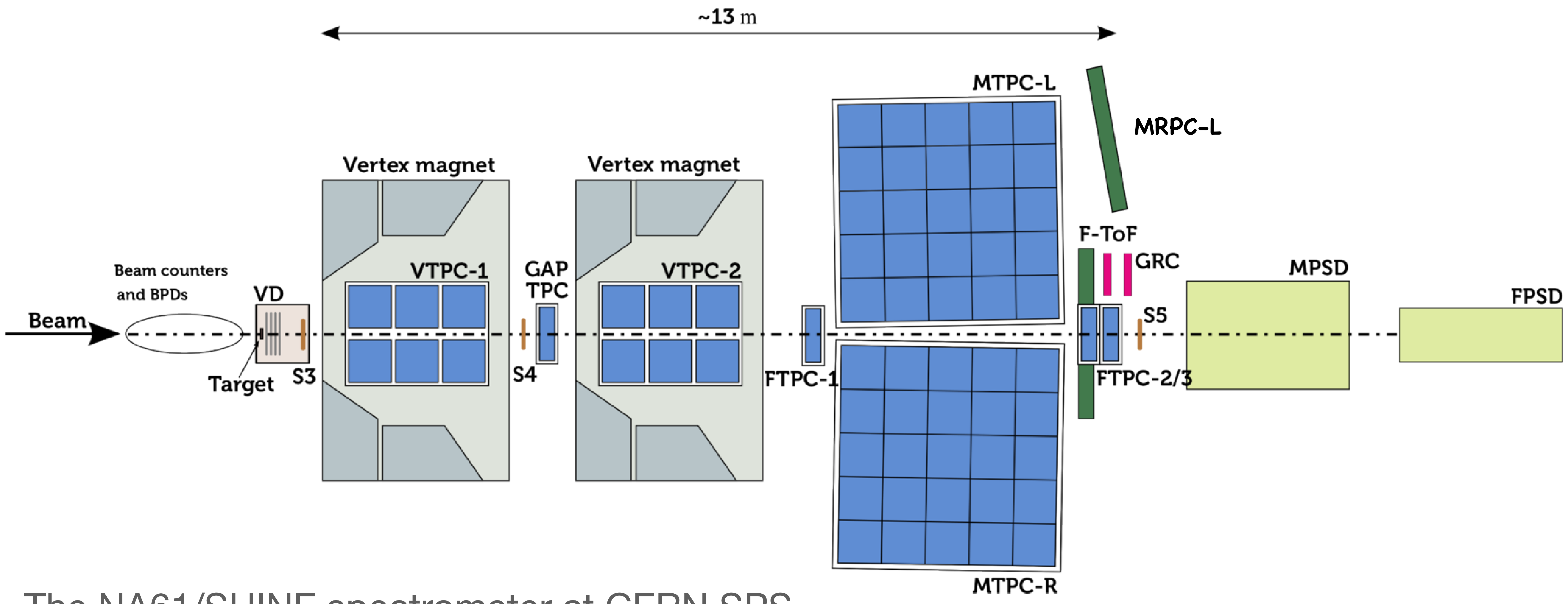
Beamline upgrade

Upgrades of the beam line to **increase the rate of statistics accumulation** for T2K-II and HK:

- Operation with a **320kA horn current** (previously 250kA) since end of 2023.
- Various **MR upgrades** to increase the beam intensity: **higher repetition** rate + **more protons** per spill
- The goal is to reach **1.3 MW** by **2028**.



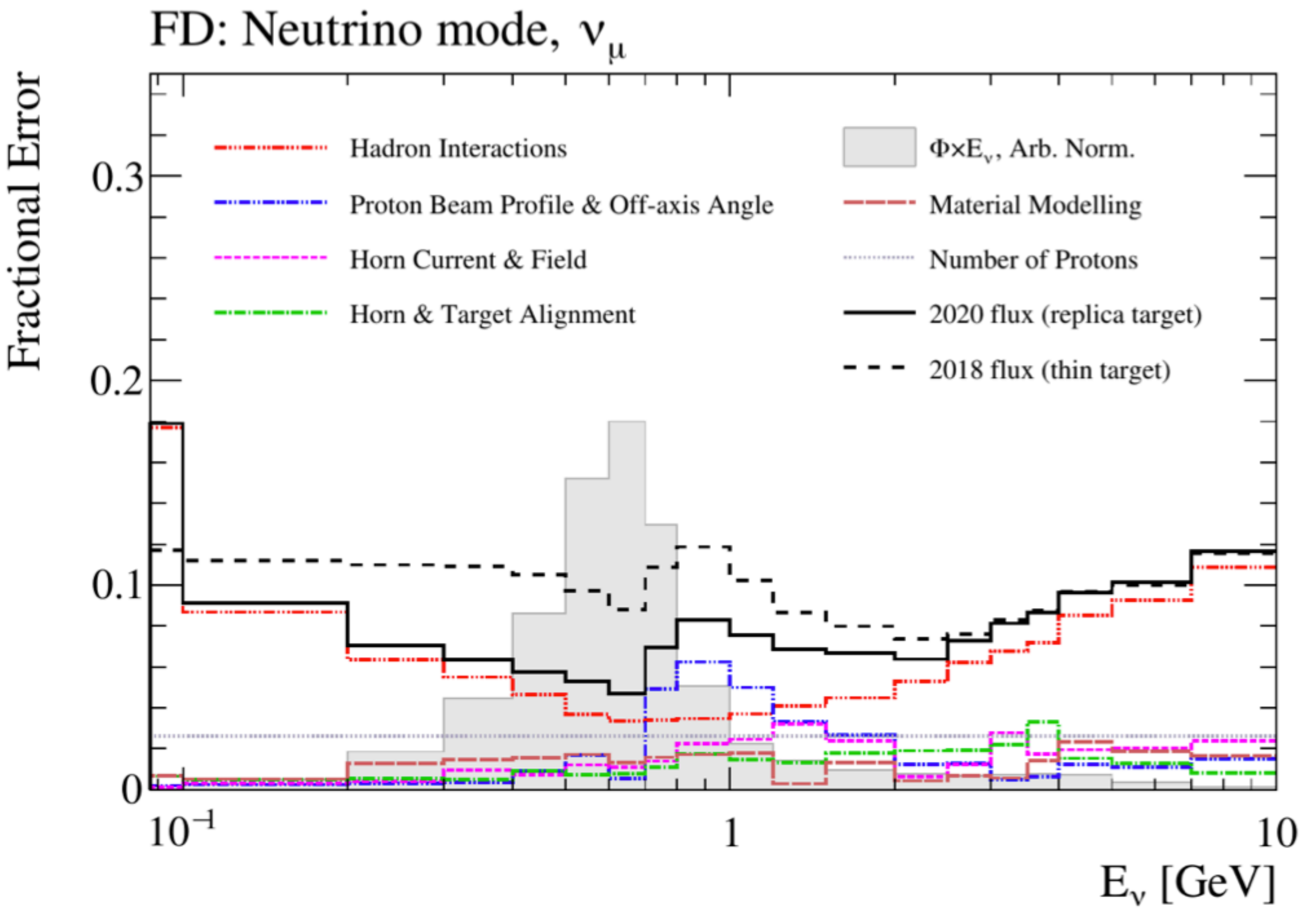
NA61/SHINE experiment: T2K replica target data



The NA61/SHINE spectrometer at CERN SPS

NA61/SHINE for T2K

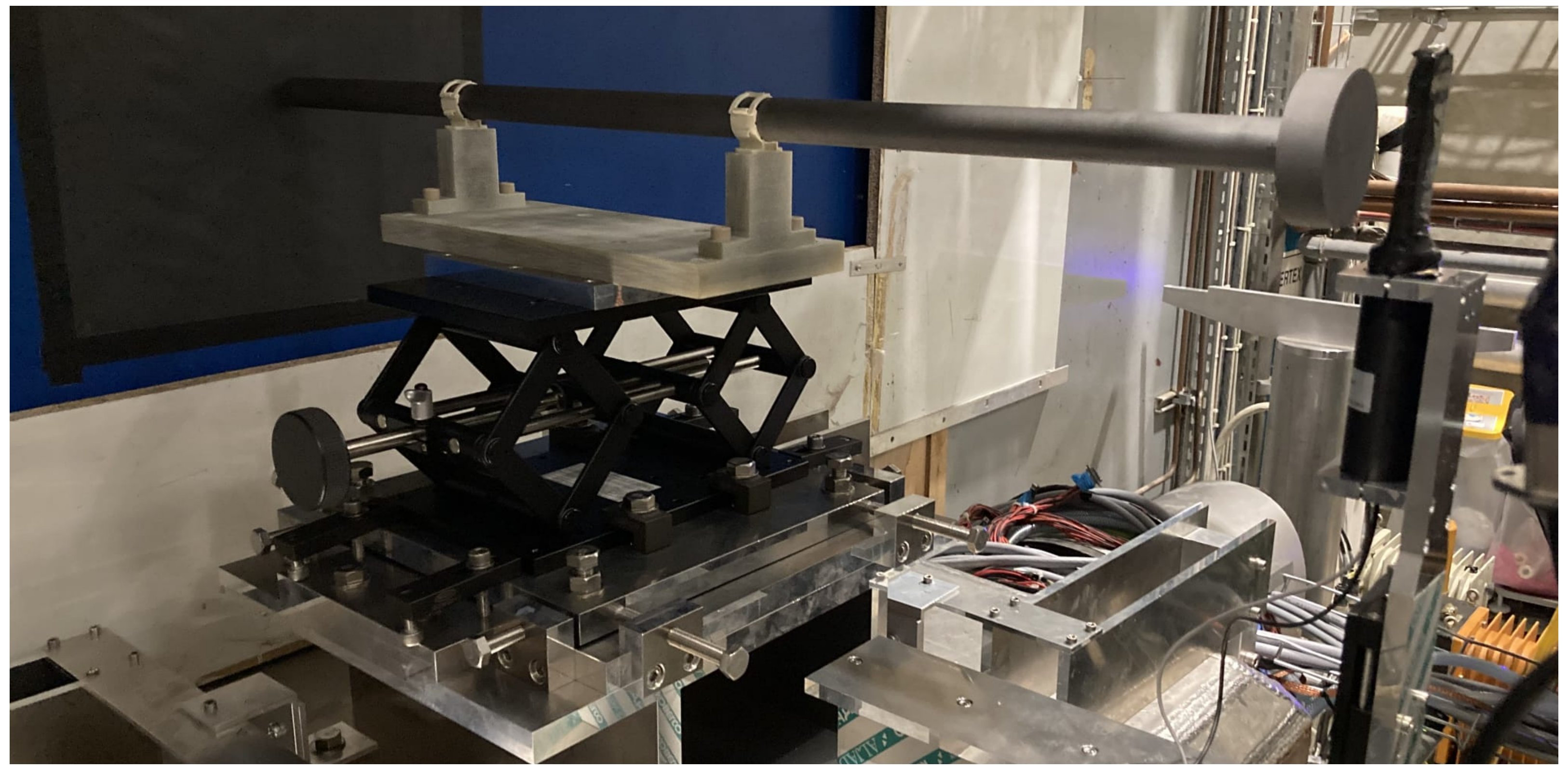
- Previous measurements allowed **reduction of neutrino flux uncertainty down to 5%** in T2K
- **Upgraded NA61/SHINE** spectrometer used to measure the **hadron yields from T2K replica target in 2022**
- New dataset is being **calibrated by French and Japanese students**
- **~10 times more statistics** than previous dataset (2010)



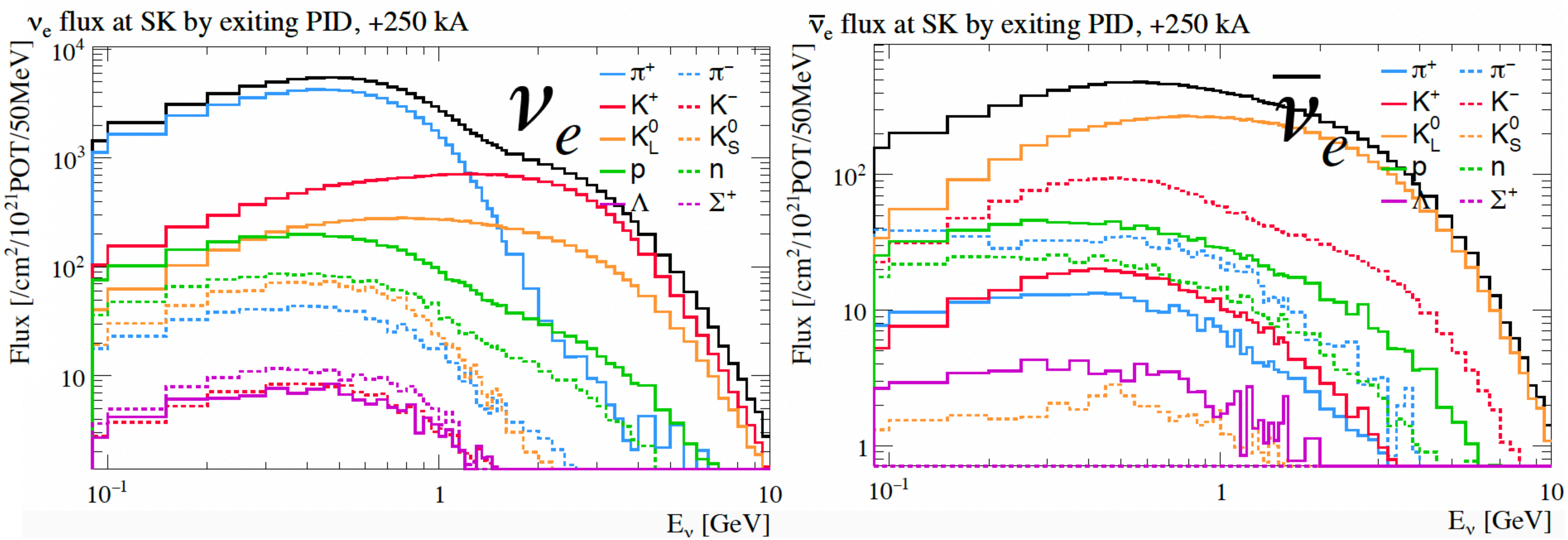
NA61/SHINE for T2K

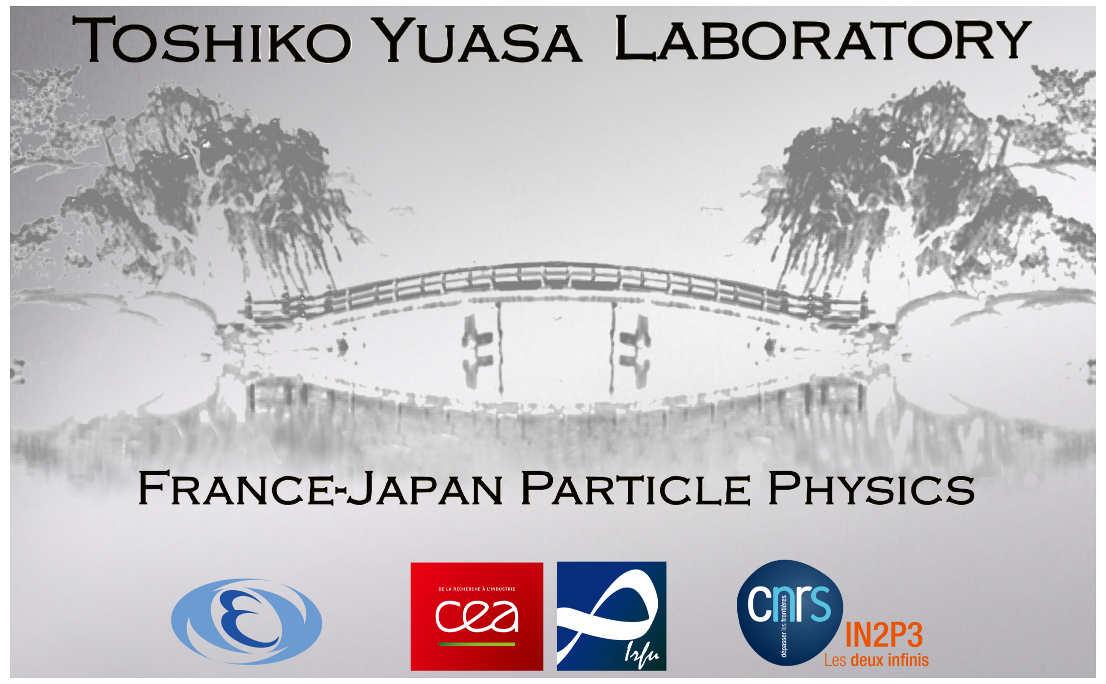
New dataset will allow:

- **Further reduction** of the $\nu_\mu/\bar{\nu}_\mu$ **flux uncertainty** in T2K
- K^0_S **yield measurement**, thanks to higher statistics, useful to better constrain $\nu_e/\bar{\nu}_e$ contamination
- **Higher energy $K^\pm$ measurement**, with the higher magnetic field dataset, useful to better constrain the high energy part of the neutrino flux



T2K replica target at NA61/SHINE





Time synchronisation in HK

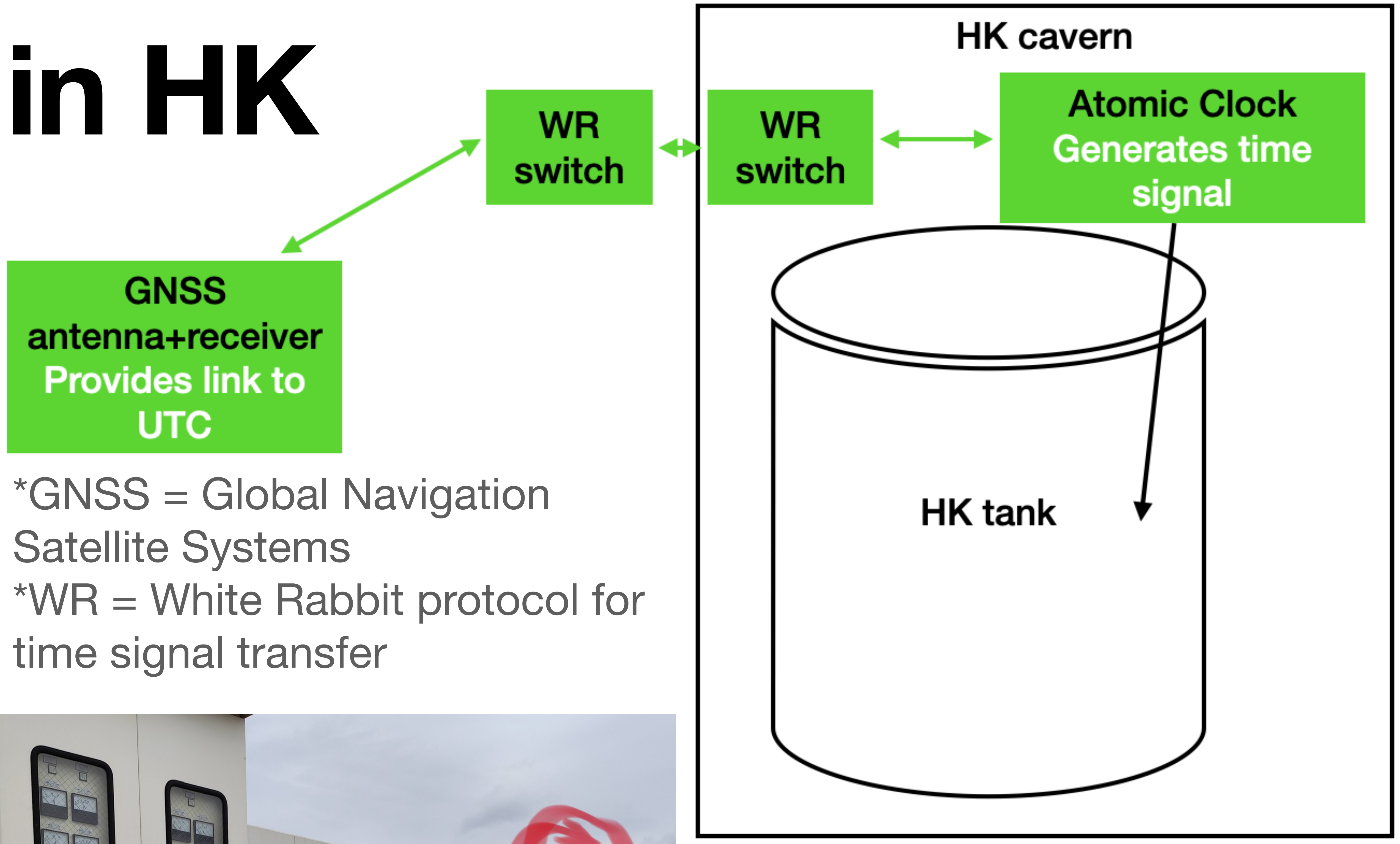
Time synchronisation in HK

- **Need external synchronisation**: with **J-PARC** and **with UTC (100 ns)** for multi-messenger programs

- **Local time** is generated by an **atomic clock** (Rubidium) which is imperfect: it drifts with respect to UTC

- **A correction method** was developed at LPNHE. We **optimised** it for our clock and **proved its efficiency** on data: NIM A 1075 (2025) 170358.

- Started **installation of antenna and receiver at J-PARC**



*GNSS = Global Navigation Satellite Systems
*WR = White Rabbit protocol for time signal transfer

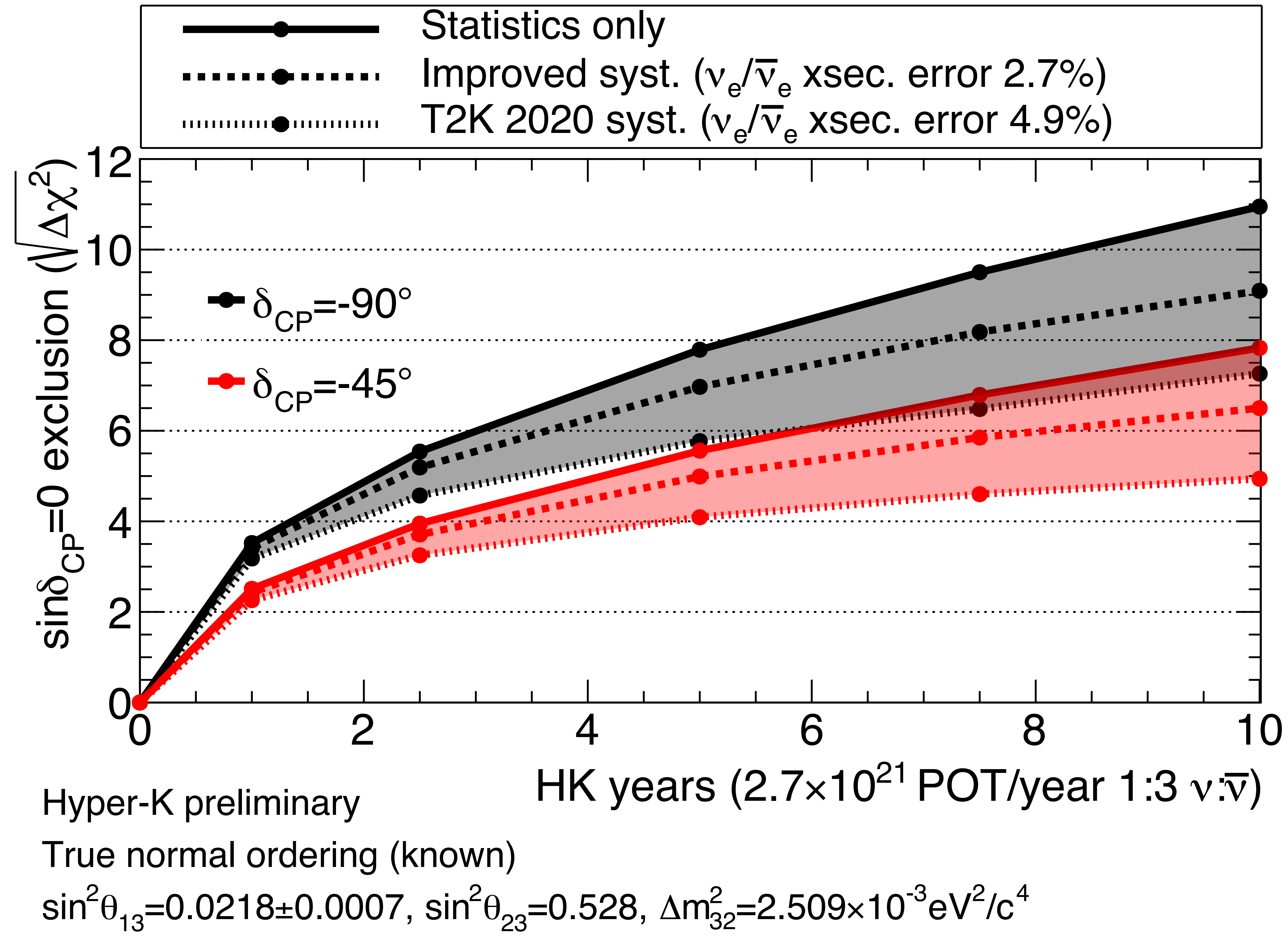
New structure for fixing antenna

Similar systems are needed at HK and J-PARC to ensure synchronisation between the two sites.

New neutrino oscillation sensitivity results for HK

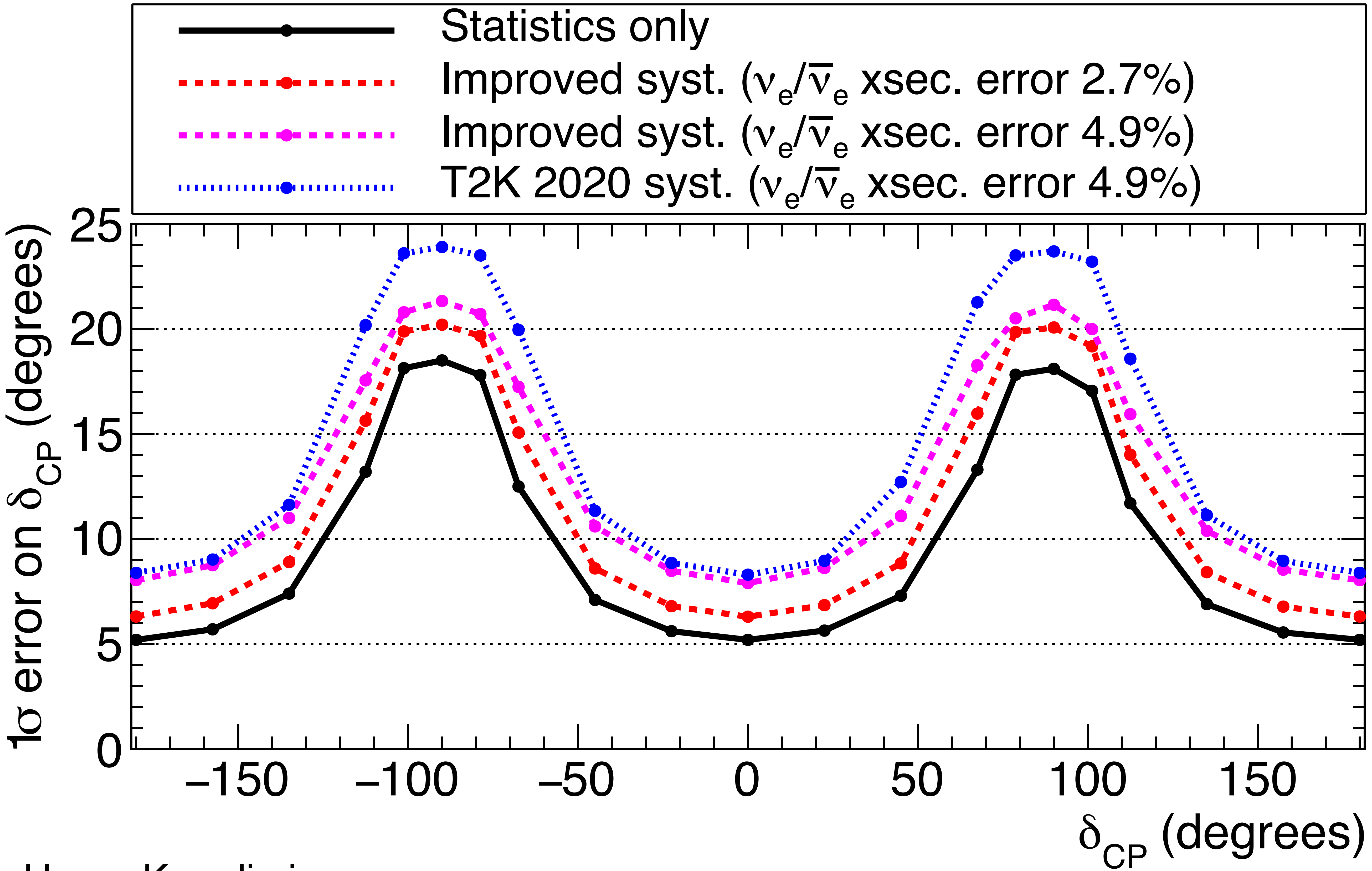
New sensitivity results for HK

- Studied the sensitivity of HK to the **precision measurement** of the PMNS **oscillation parameters** with the accelerator beam neutrinos with focus on **CP violation phase** δ_{CP}
- Used a frequentist fitter framework from T2K on simulated data:
  - Rescaled T2K MC to match **HK's statistics**
  - **Optimised the framework** to work better on larger statistics
  - Included **improved uncertainties** (taking into account beam line upgrade and NA61/SHINE future results)
- Accelerator beam only results are **official** (talk at NNN 2023, and EPS 2025) and a **paper is in preparation**



New sensitivity results for HK

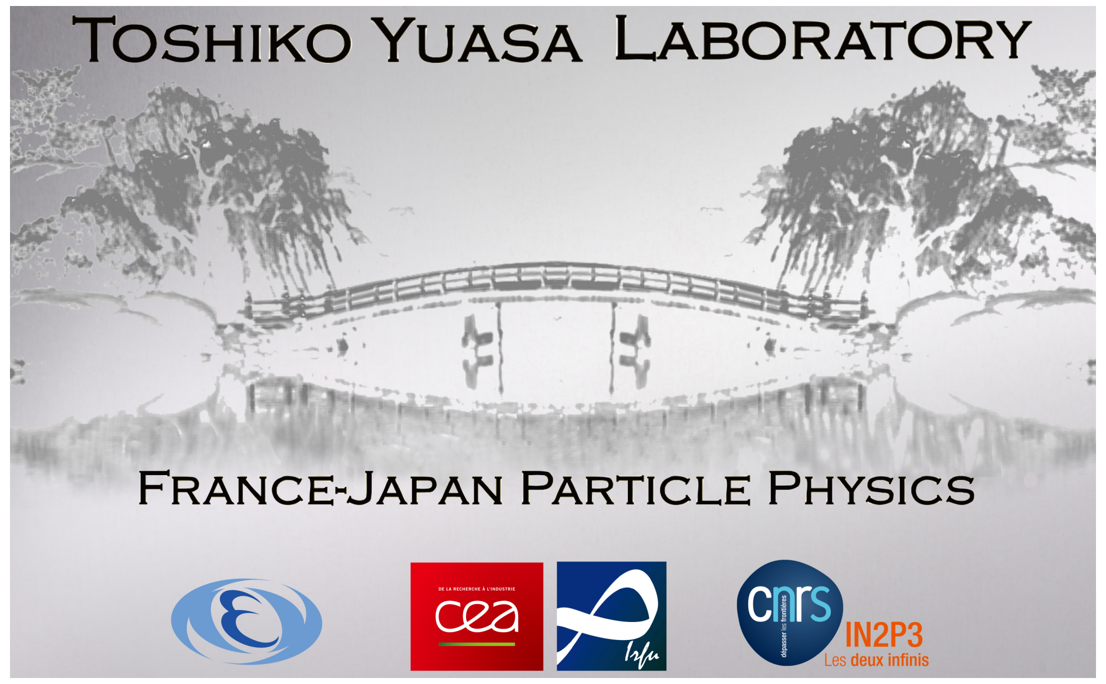
- Studied which **systematics** will become limiting
- Example here of impact of the uncertainty on the ratio $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ depending on true value of δ_{CP}
- Important for the **development/ upgrade of near detectors** and for the **development of systematic model**



Hyper-K preliminary

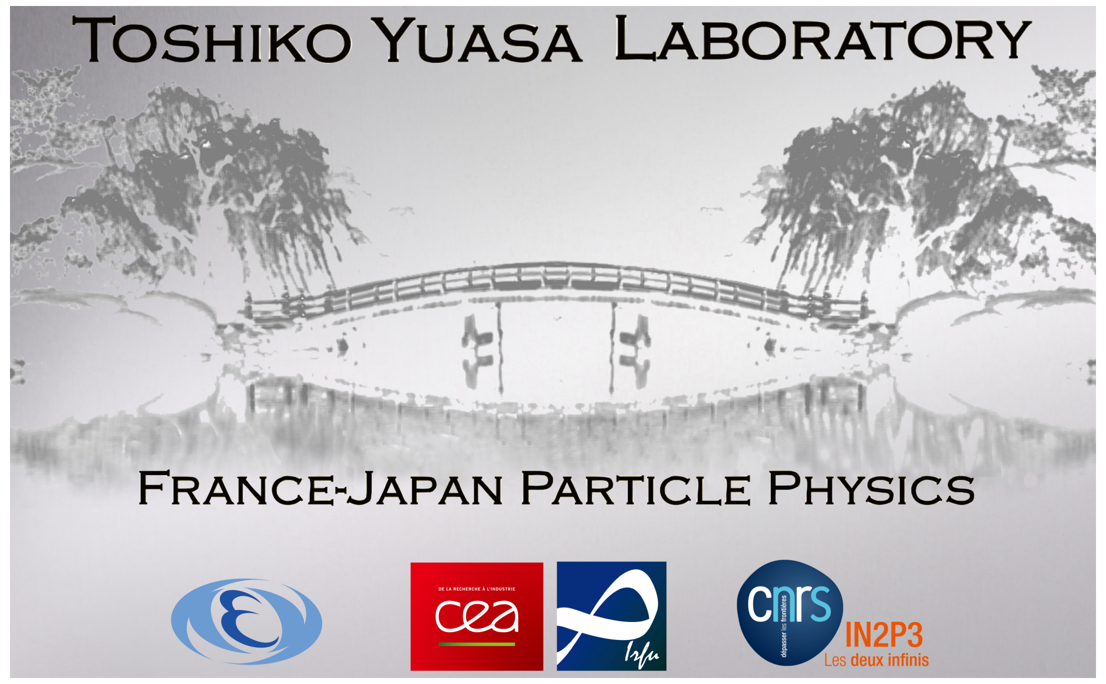
True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 $\nu:\bar{\nu}$)

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



Conclusions

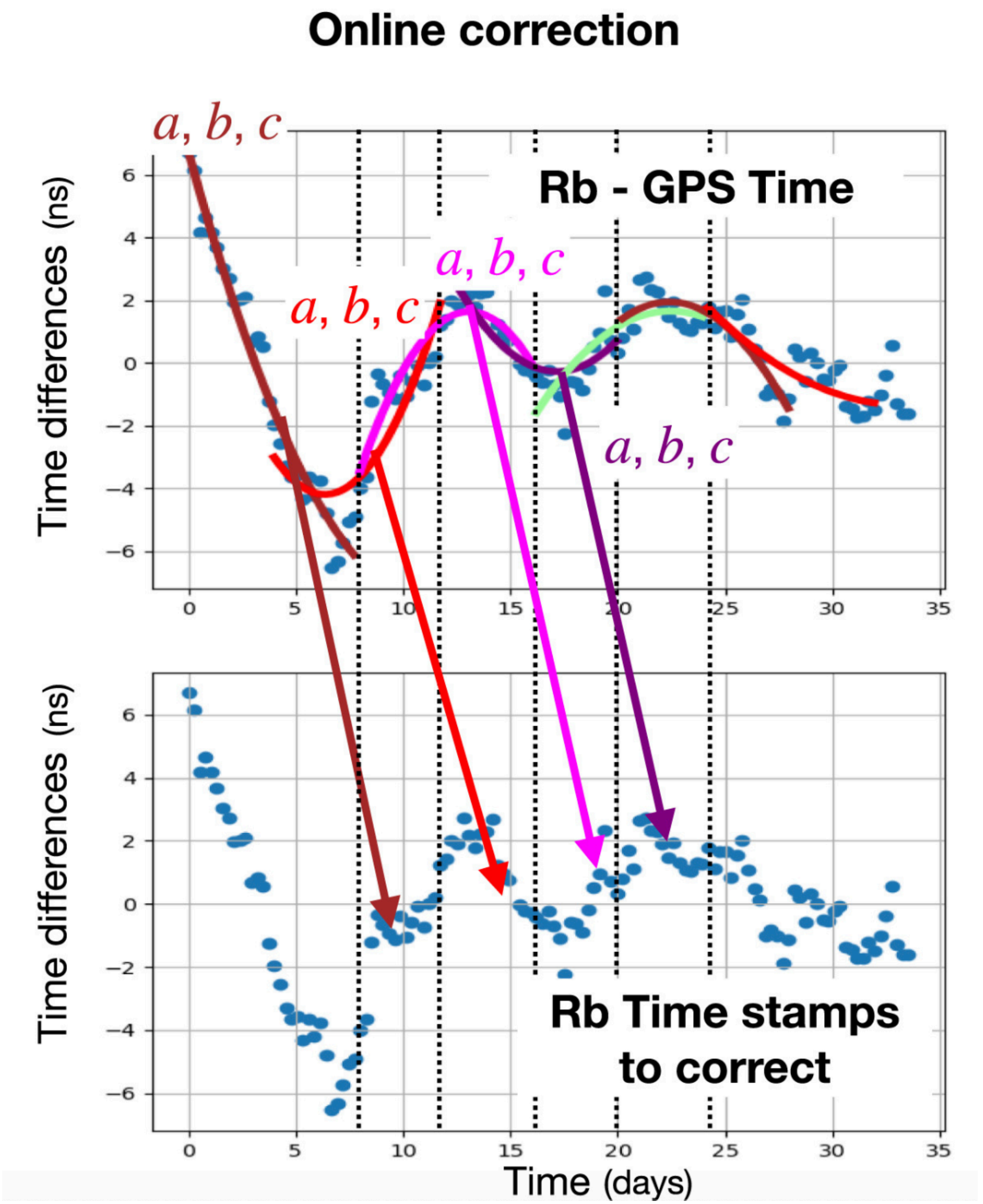
Conclusions



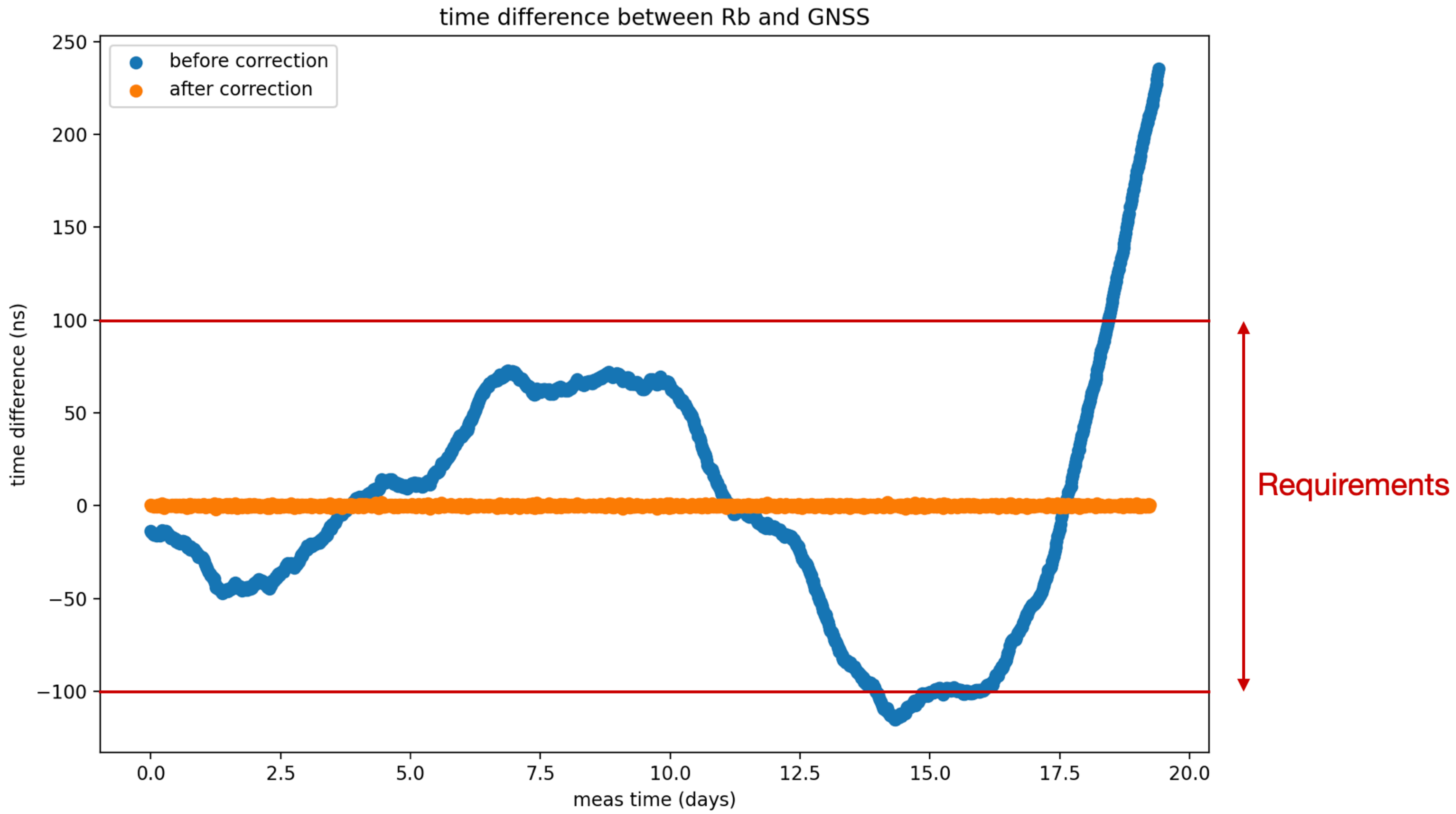
- The NU-09 project is an **active** project with **great France-Japan collaboration** and **ambitious** scientific goals
- **Important recent achievements**:
    - J-PARC neutrino **beam line upgrades**, still ongoing
    - New **NA61/SHINE T2K replica target** data (2022) being analysed by Japanese and French members
    - Milestones on the **synchronisation system for HK**: NIM A publication in 2025, start of installation at J-PARC and HK sites
    - **New sensitivity studies** for the neutrino oscillation parameters measurement with accelerator neutrinos, soon to be published
- **Many more results to come: discovery potential (e.g., CP violation)!**

Thank you!

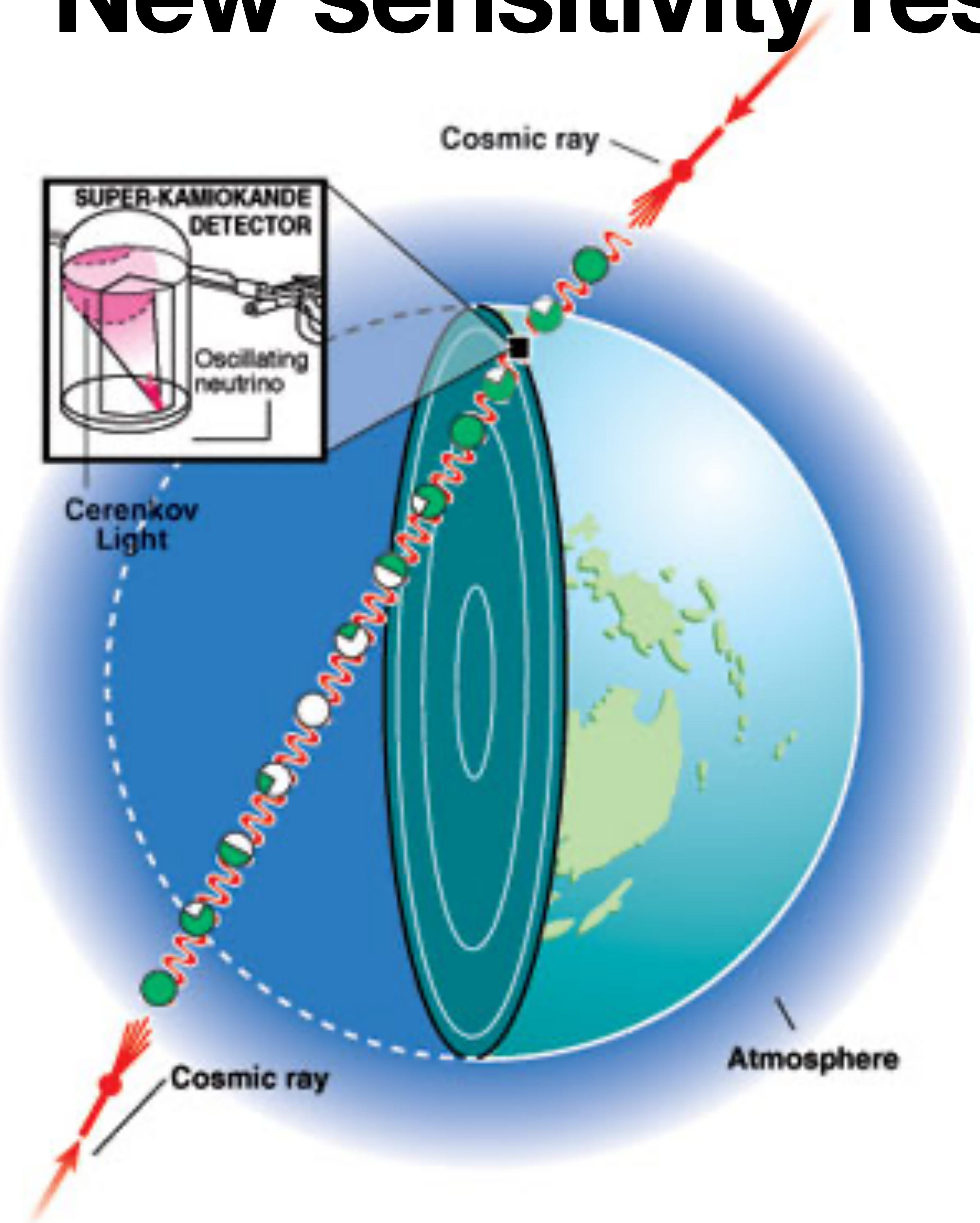
Time synchronisation in HK

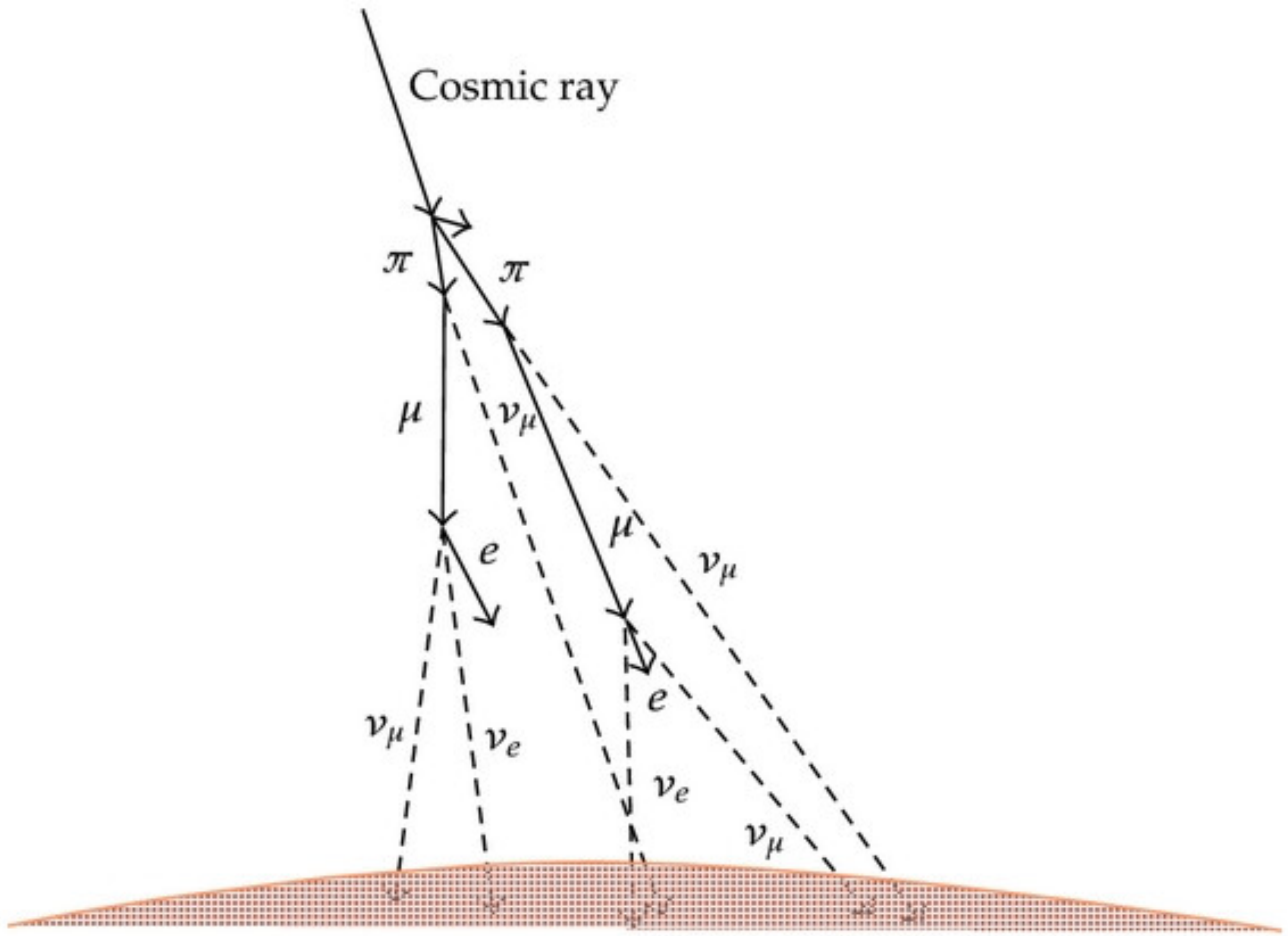


Use the Rb - UTC **measured by the GNSS receiver** to **predict the near future drift** of the clock and **correct** it



New sensitivity results for HK



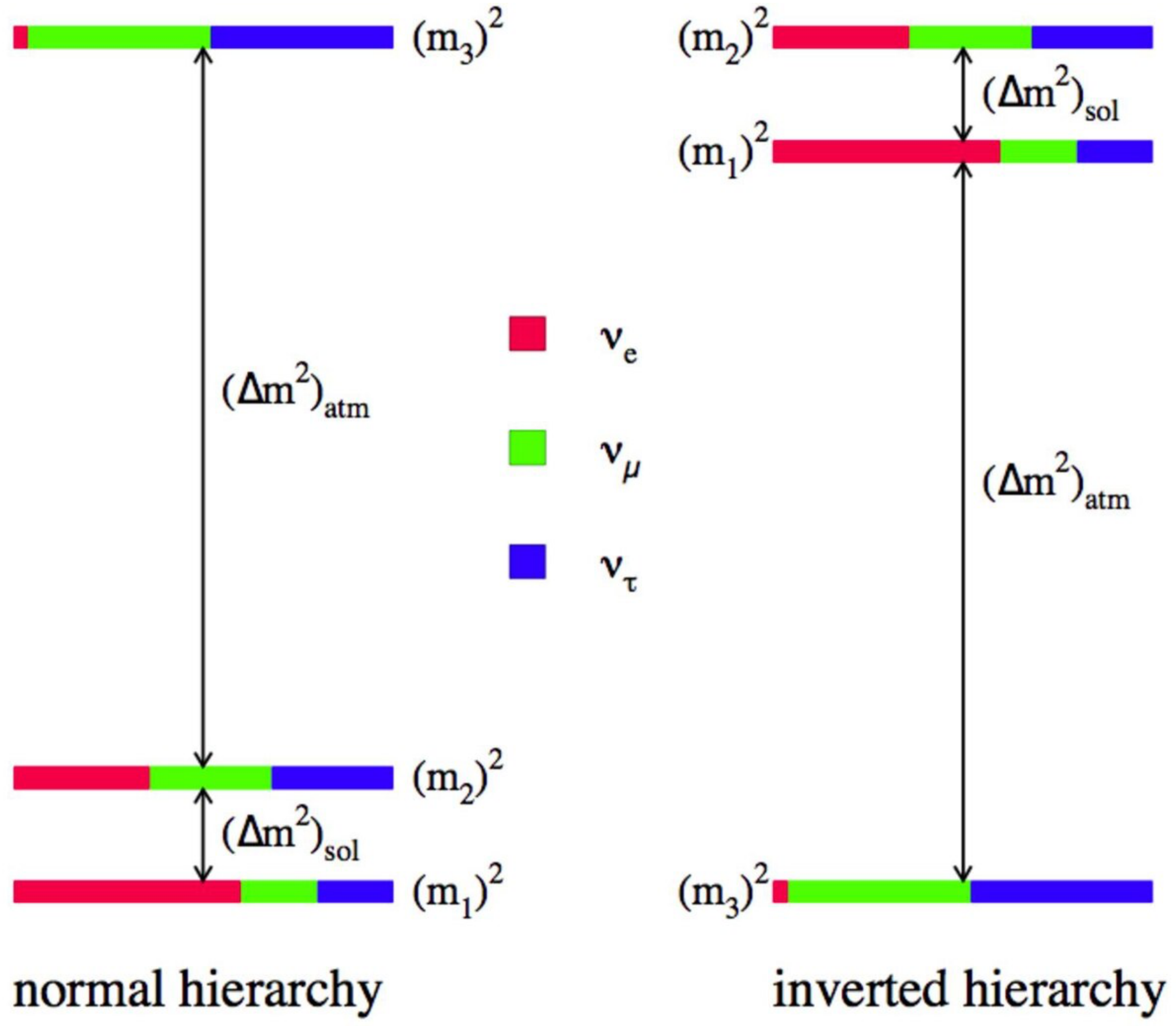


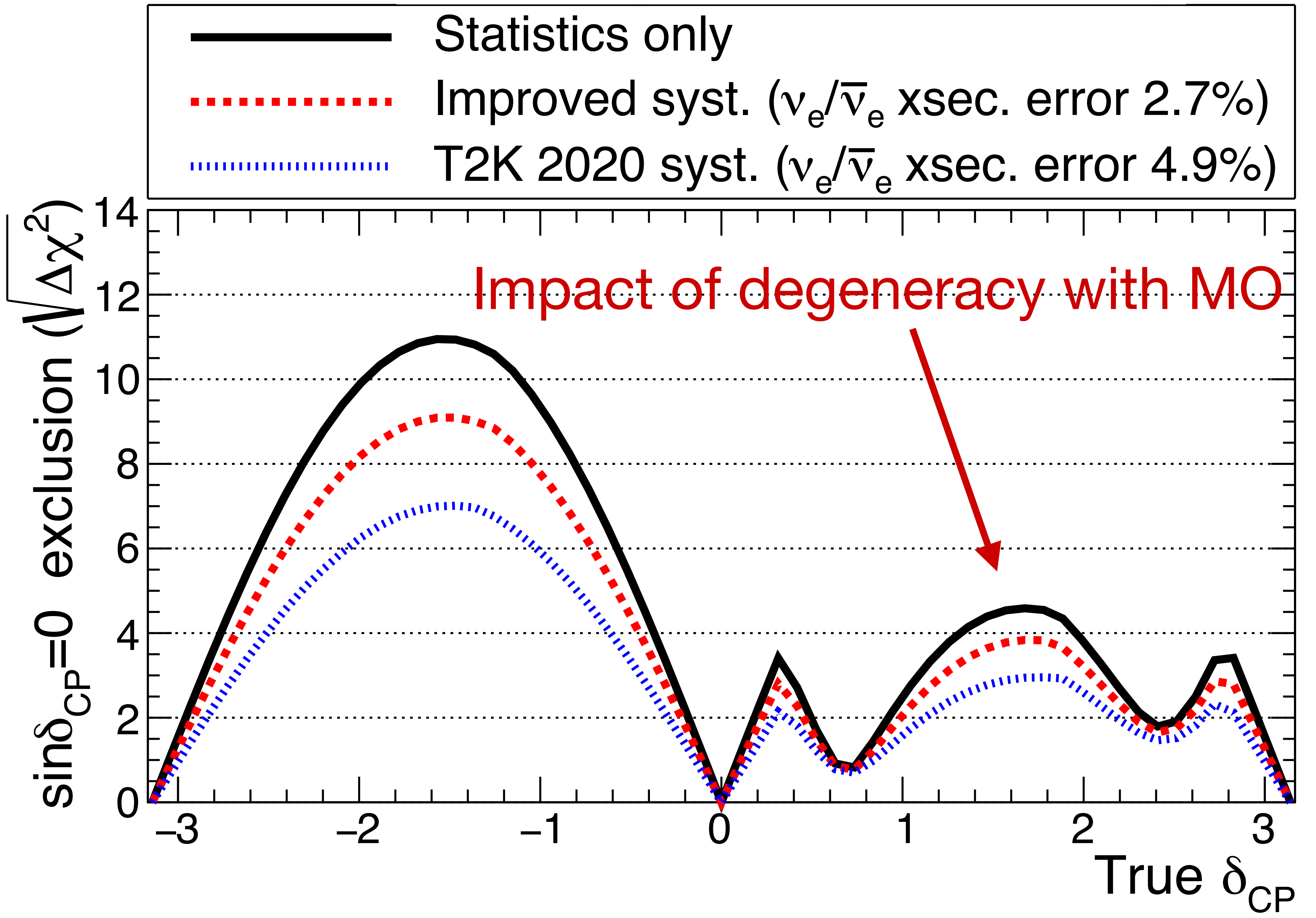
Atmospheric neutrinos: twice as many ν_μ ($\bar{\nu}_\mu$) as ν_e ($\bar{\nu}_e$).
Compare flavour composition in upward-going and downward-going neutrinos.

New sensitivity results for HK

Next step: include **atmospheric** neutrinos samples

- To **lift degeneracy** between δ_{CP} and **Mass Ordering** (MO)
- **Prepare** the joint analysis **framework**
- Important at the beginning of HK, **when MO is not yet known**
- **First published T2K-SK results in 2025**: Phys. Rev. Lett. 134 (2025) 011801





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