Towards Hyper-Kamiokande analyses

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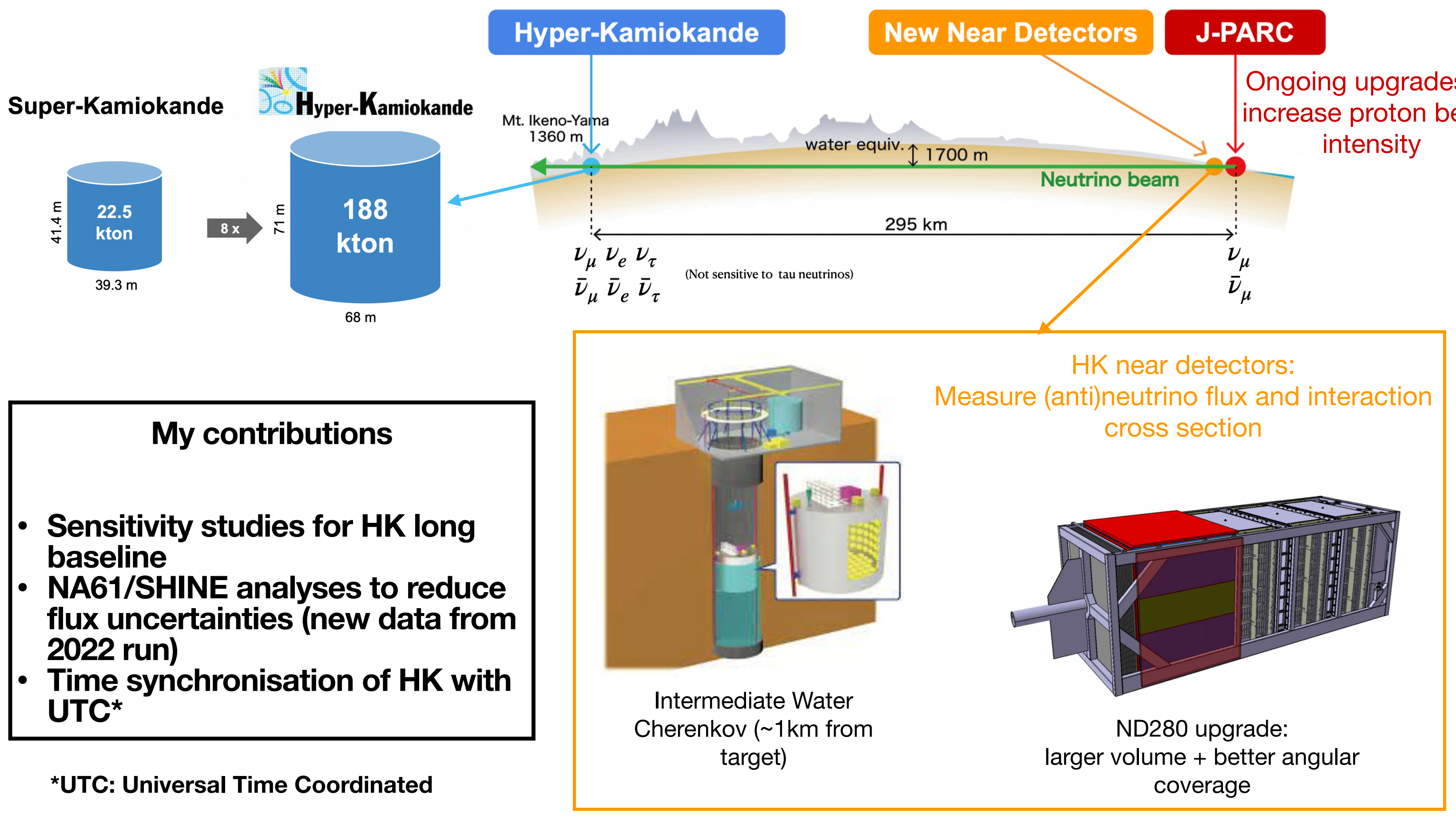
From T2K to Hyper-Kamiokande (HK)



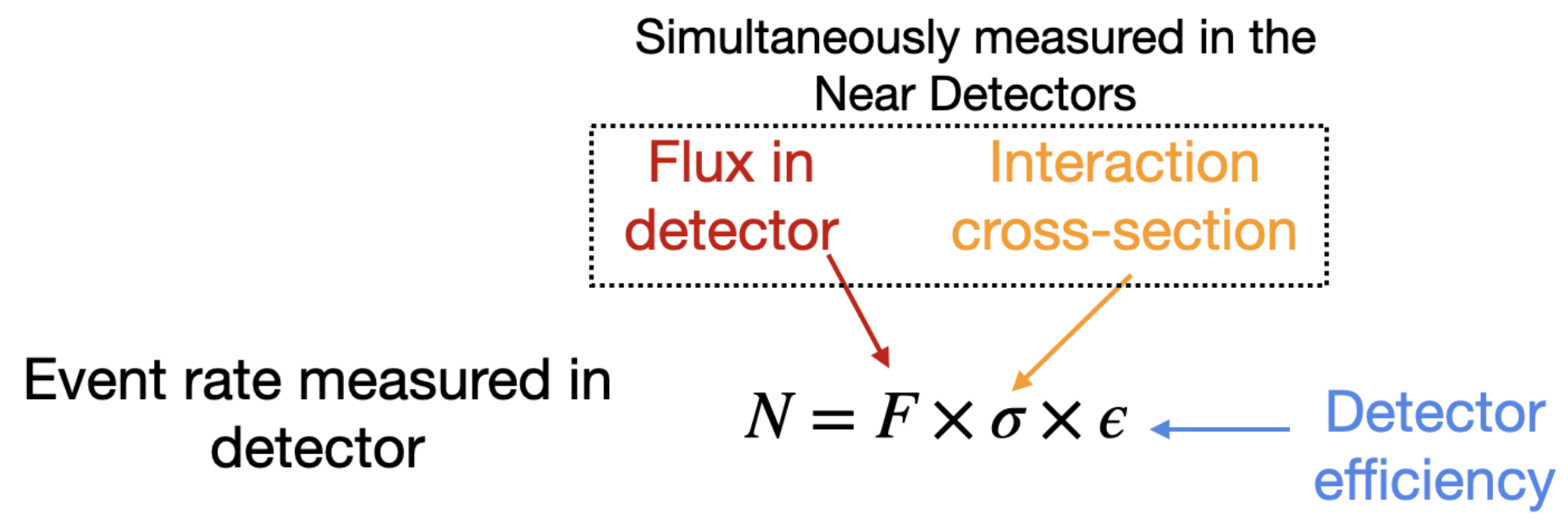
My contributions

- **Sensitivity studies for HK long baseline**
- **NA61/SHINE analyses to reduce flux uncertainties (new data from 2022 run)**
- **Time synchronisation of HK with UTC***

***UTC: Universal Time Coordinated**

*Figure 1. The Hyper-Kamiokande [2] detector is being built in Japan and the **data-taking is planned to start in 2027**. The HK long baseline program will use the same neutrino beam as T2K but a bigger far detector with the same off-axis angle of 2.5°. The neutrino flux will be well characterized thanks to NA61/SHINE [1] hadron production measurements and by a set of Near Detectors, including ND280 upgrade and IWCD.*

With an accumulation of statistics approximately 10 times faster compared to T2K, **HK will soon become limited by systematic effects**. **NA61/SHINE hadro-production measurements** already allowed to greatly **reduce the neutrino flux uncertainties** as shown in Figure 3. **New data has been collected using T2K replica target** in summer 2022 and are being analyzed.



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

Figure 2. Three types of systematic parameters in T2K.

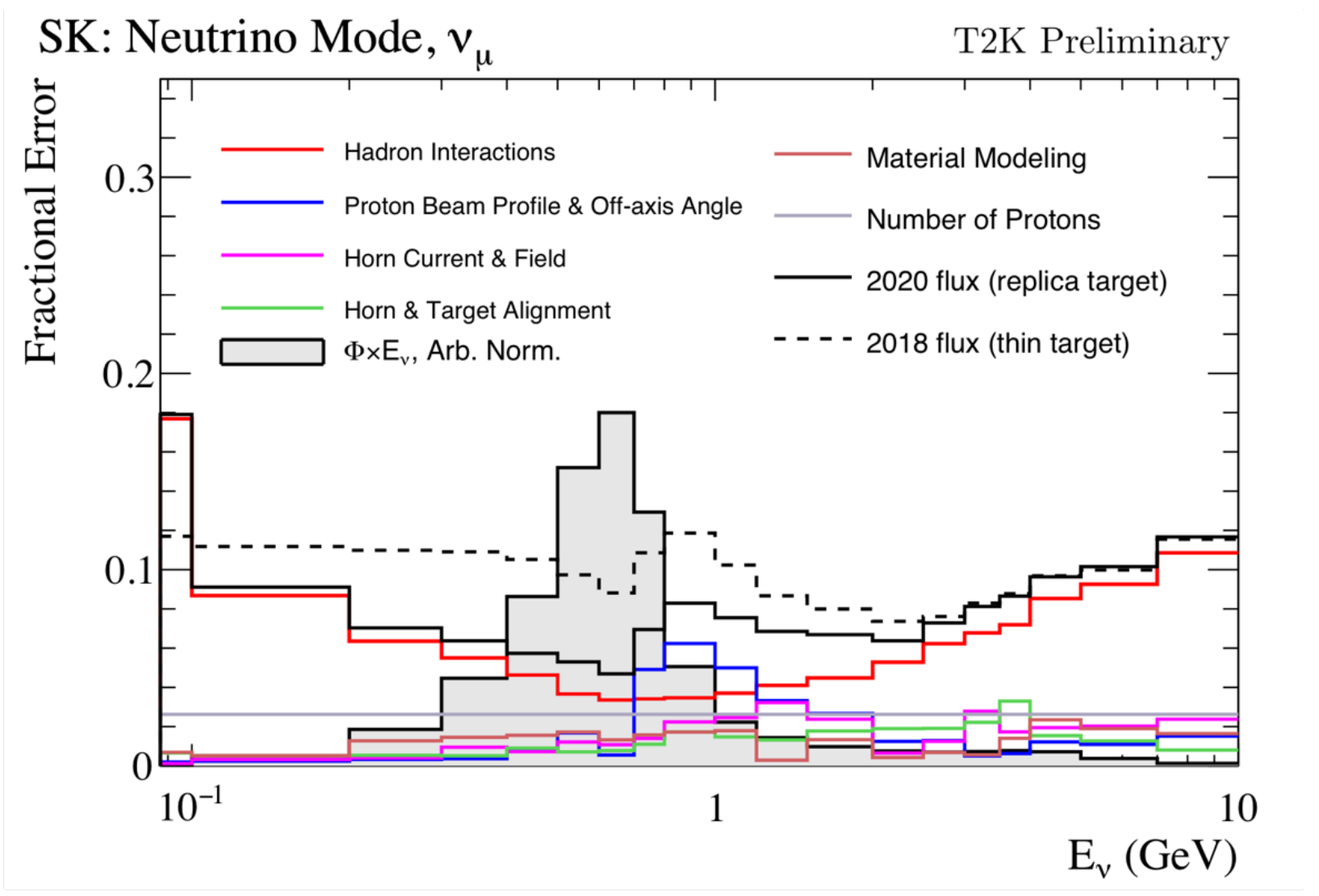


Figure 3. Current T2K flux uncertainties on the event rates in SK and impact of NA61/SHINE hadron production measurements with the T2K replica target.

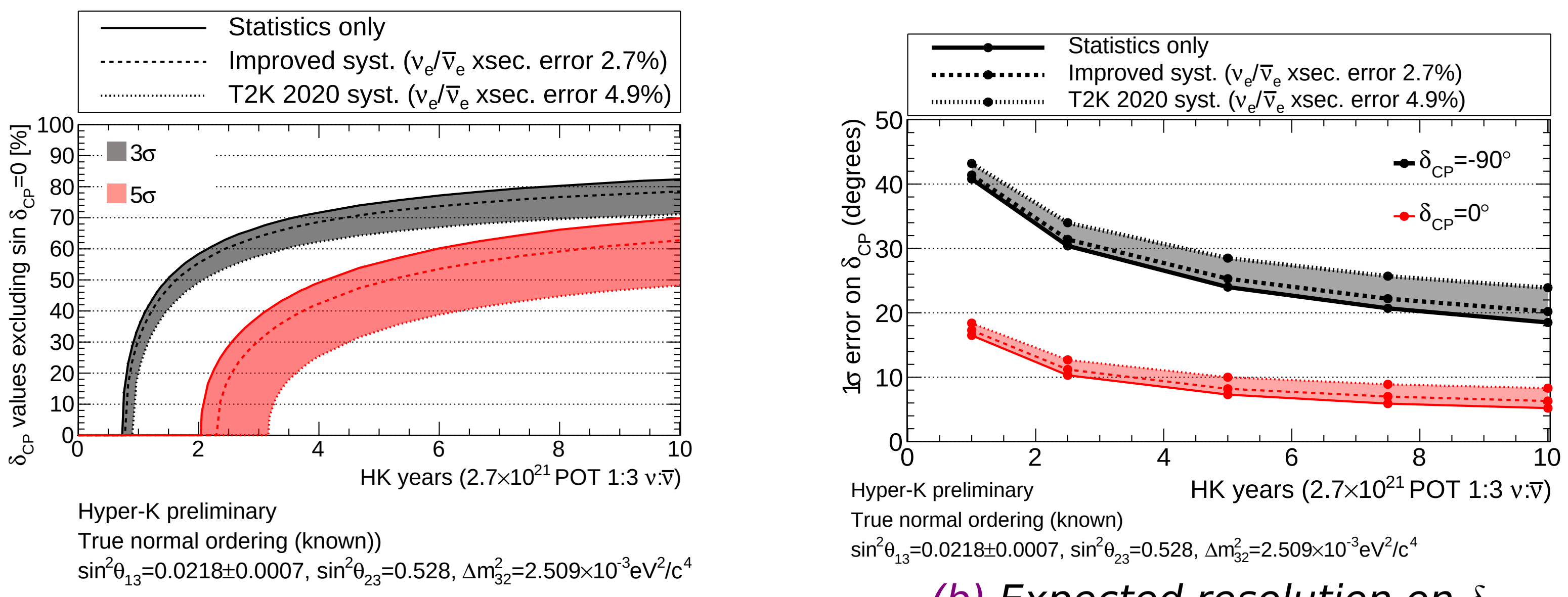
Sensitivity studies for Hyper-Kamiokande

Produced new sensitivity studies using the latest published T2K results [3]. Three scenarios of systematic uncertainties are considered:

- Statistics only: no systematic uncertainties
- T2K 2020 syst.: same level of uncertainties as in [3]
- Improved syst.: estimation for HK

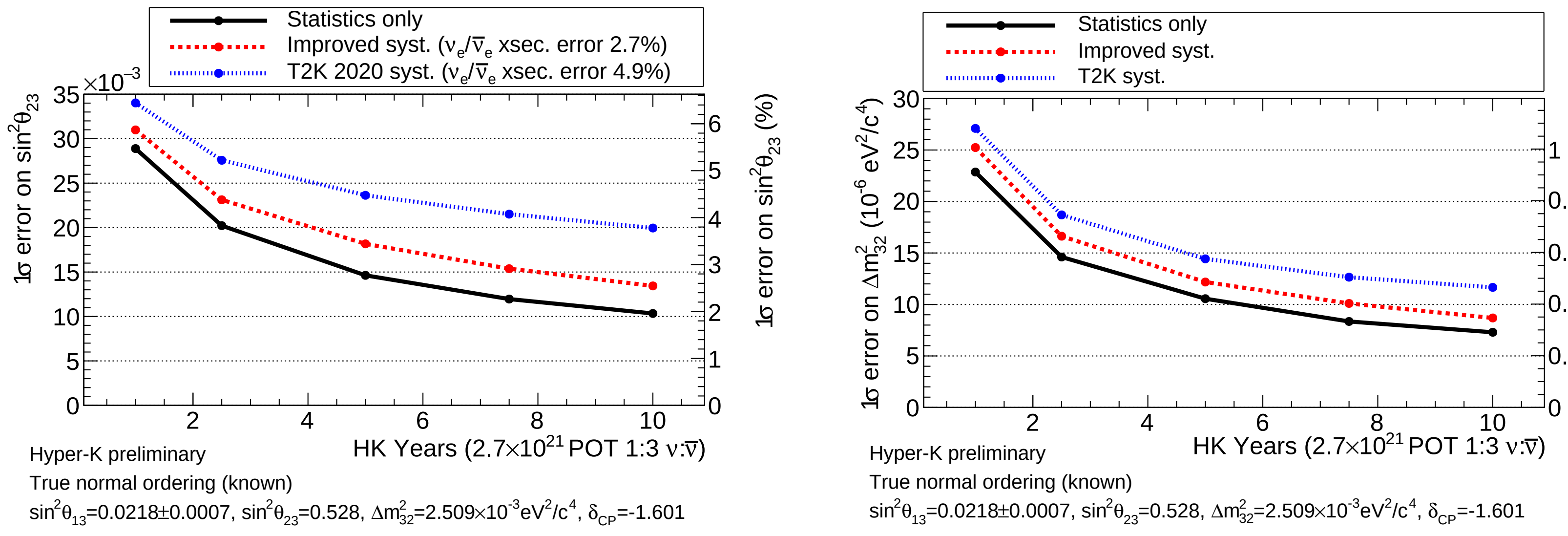
T2K 2020 (Imp.) syst.	ν-mode e-like	ν-mode μ-like	$\bar{\nu}$-mode e-like	$\bar{\nu}$-mode μ-like
ND constrained				
Flux+cross section	3.6% (1.8%)	2.1% (0.9%)	4.3% (1.6%)	3.4% (0.9%)
Not ND constrained				
Cross section	3.0% (1.6%)	0.5% (0.4%)	3.7% (1.4%)	2.6% (0.4%)
Detector	3.1% (1.1%)	2.1% (0.8%)	3.9% (1.5%)	1.9% (0.7%)
All	4.7% (2.1%)	3.0% (1.2%)	5.9% (2.2%)	4.0% (1.1%)

Table 1. 1σ uncertainty on the expected number of events in HK with the T2K 2020 or Improved error model. The Improved error model was built by shrinking the individual systematic uncertainties from T2K 2020 systematic error model to take into account the expected effects of the upgrades and the statistics increase.



(a) Expected $\sin(\delta_{CP}) = 0$ exclusion

(b) Expected resolution on δ_{CP}



(c) Expected resolution on $\sin^2\theta_{23}$

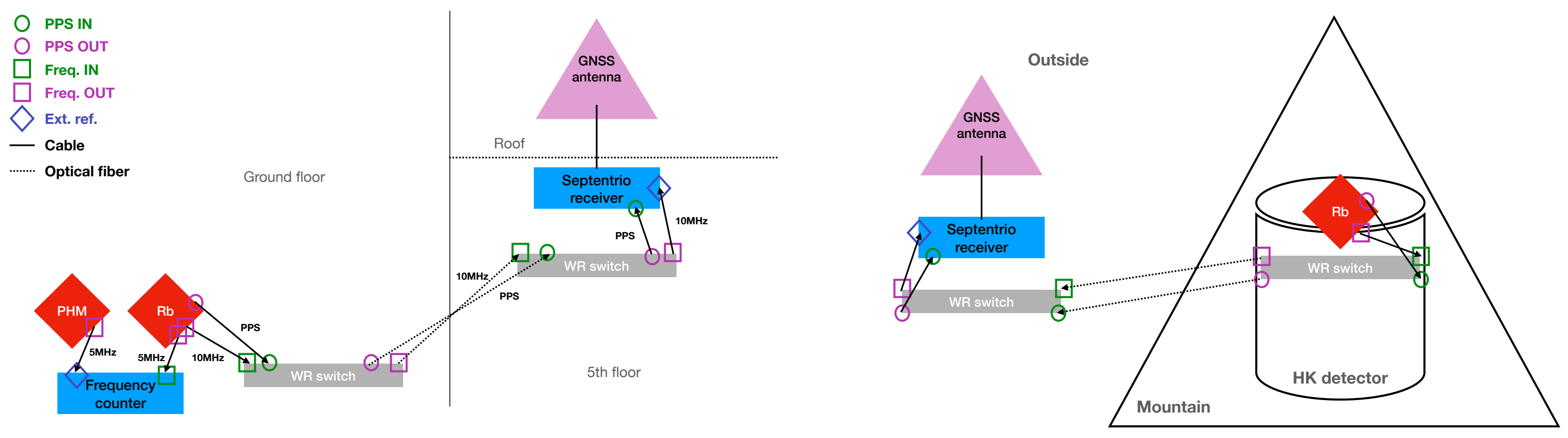
(d) Expected resolution on Δm^2_{32}

Figure 4. Prediction of HK sensitivity to oscillation parameters: impact of the statistics and the systematic uncertainties.

In case of maximal CP violation, $\sin\delta_{CP} = 0$ **will be excluded in less than 3 years**. After 10 years, if the systematic uncertainties are reduced compared to T2K, HK will **exclude CP conservation at 3 (5) sigma for 80% (60%) of the possible δ_{CP} values. δ_{CP} could be measured with a less than 20° precision** and the resolution would reach a **few percent and less than a percent for $\sin^2\theta_{23}$ and Δm^2_{32}** respectively.

Time synchronisation of HK with UTC

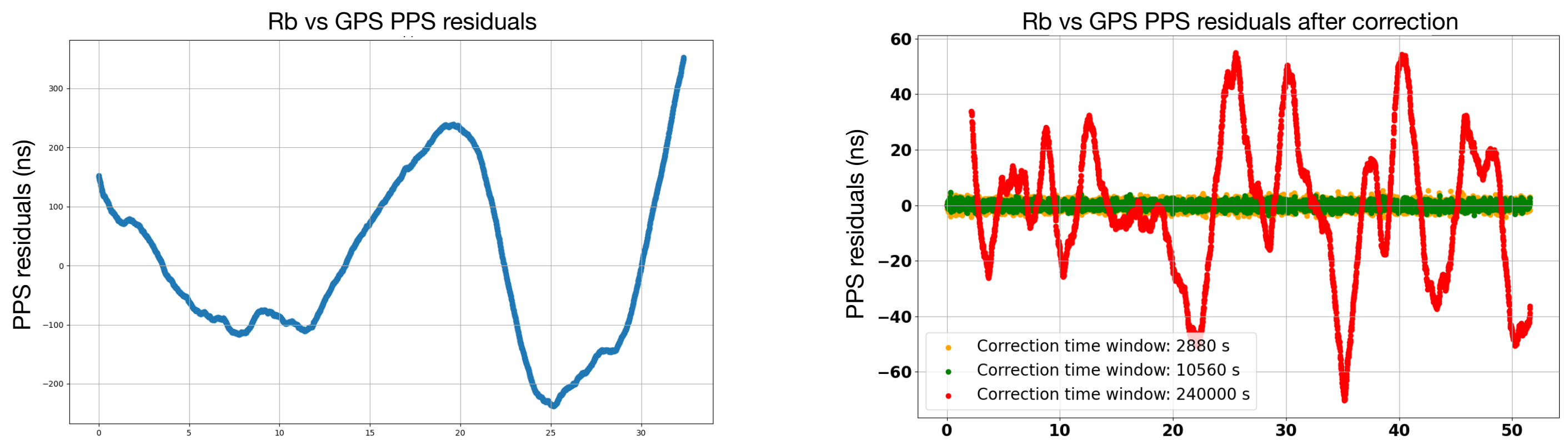
The HK detector needs to be synchronized with UTC to time stamp the event detected **with a precision better than 100 ns**. For the long baseline program, this allows to tag the accelerator neutrinos. For the multi-messenger, it allows to send warning to other experiments. For instance, in the framework of the SuperNova Early Warning System (**SNEWS**), HK will send an alarm in case of detection of neutrinos from a SuperNova and pinpoint to the direction of this SuperNova.



(a) Setup at LPNHE

(b) Foreseen setup at HK

*Figure 5. **The time signal in HK will be generated by a free-running Rubidium atomic clock** inside the cavern and continuously compared to Global Navigation Satellite Systems (GNSS) time signals thanks to an antenna outside of the cavern. The real time corrections of the event time stamps will be derived from those comparisons. A similar setup has been installed at LPNHE with the addition of a "control system" composed of a frequency counter and another more stable (and more expensive) atomic clock called Passive Hydrogen Maser (PHM). This allows to cross-check the stability of the corrected signal against the PHM signal.*



(a) Before Correction

(b) After Correction

*Figure 6. The time difference between GPS signals and the Rubidium clock signal was measured at LPNHE during $\sim$ 50 days. **Without any correction (see left panel), the Rubidium signal follows a random walk type of noise** and it can shift away form the GPS signals by more than 100 ns. **The uncorrected system does not fulfill the synchronisation requirement**. The correction consists in fitting the left distributions over a certain time window to predict the near future behaviour of the Rubidium signal. The fits are renewed every time we get a new comparison between Rubidium and GPS (every 16 minutes). With a short enough time window of the fits, **we can correct the random walk behaviour of the Rubidium signal (see right panel) and make sure it meets the synchronisation requirements for HK**. The optimal time window seems to be around 3 hours. See **Vincent Voisin**'s poster for more details on how to apply this method for synchronisation to UTC.*

References

[1] N. Abgrall et al. *NA61/SHINE facility at the CERN SPS: beams and detector system*. 2014. DOI: `10.1088/1748-0221/9/06/P06005`. arXiv: `1401.4699 [physics.ins-det]`.

[2] Hyper-Kamiokande Proto-Collaboration. *Hyper-Kamiokande Design Report*. 2018. arXiv: `1805.04163 [physics.ins-det]`.

[3] The The T2K Collaboration et al. "Measurements of neutrino oscillation parameters from the T2K experiment using 3.6×10^{21} protons on target". In: *Eur. Phys. J.* (Sept. 2023), p. 83.

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