Towards Hyper-Kamiokande analyses

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On behalf of the LPNHE neutrino group

From T2K to Hyper-Kamiokande (HK)

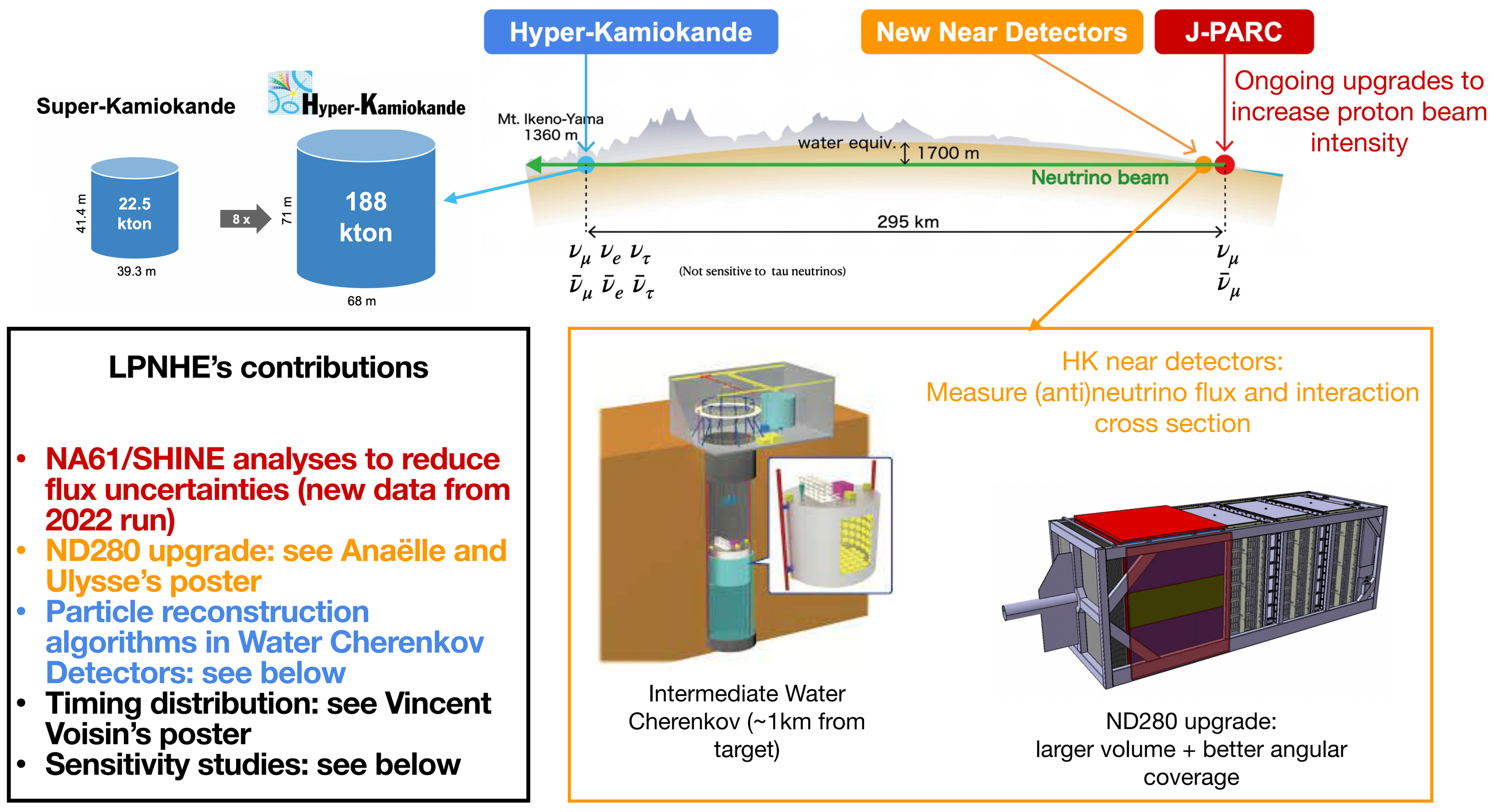


*Figure 1. The Hyper-Kamiokande [2] detector is being built in Japan and the **data-taking is planned to start in 2027**. The HK long baseline program will use the same neutrino beam as T2K but a bigger far detector with the same off-axis angle of 2.5°. The neutrino flux will be well characterized thanks 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. **The LPNHE neutrino team contributes to reducing all sources of systematic uncertainties.**

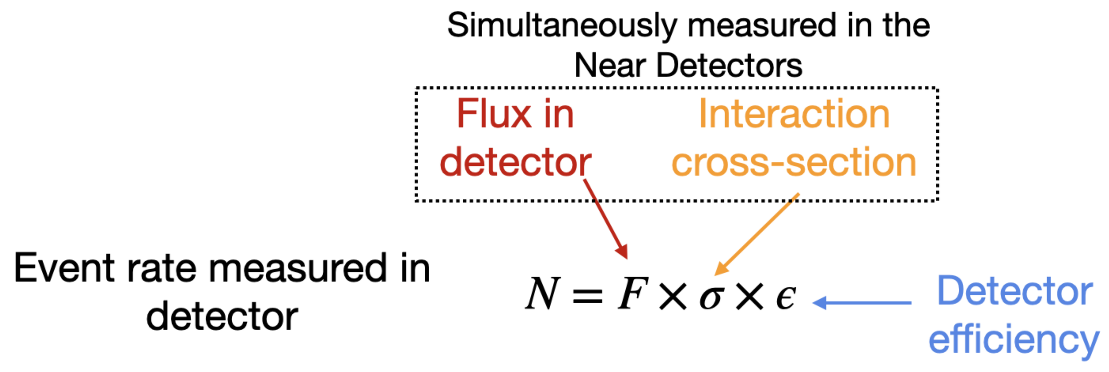


Figure 2. Three types of systematic parameters in T2K.

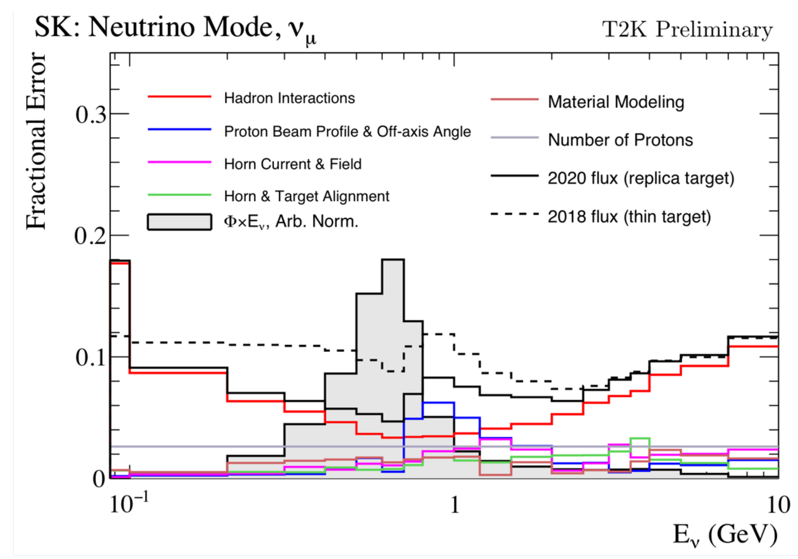


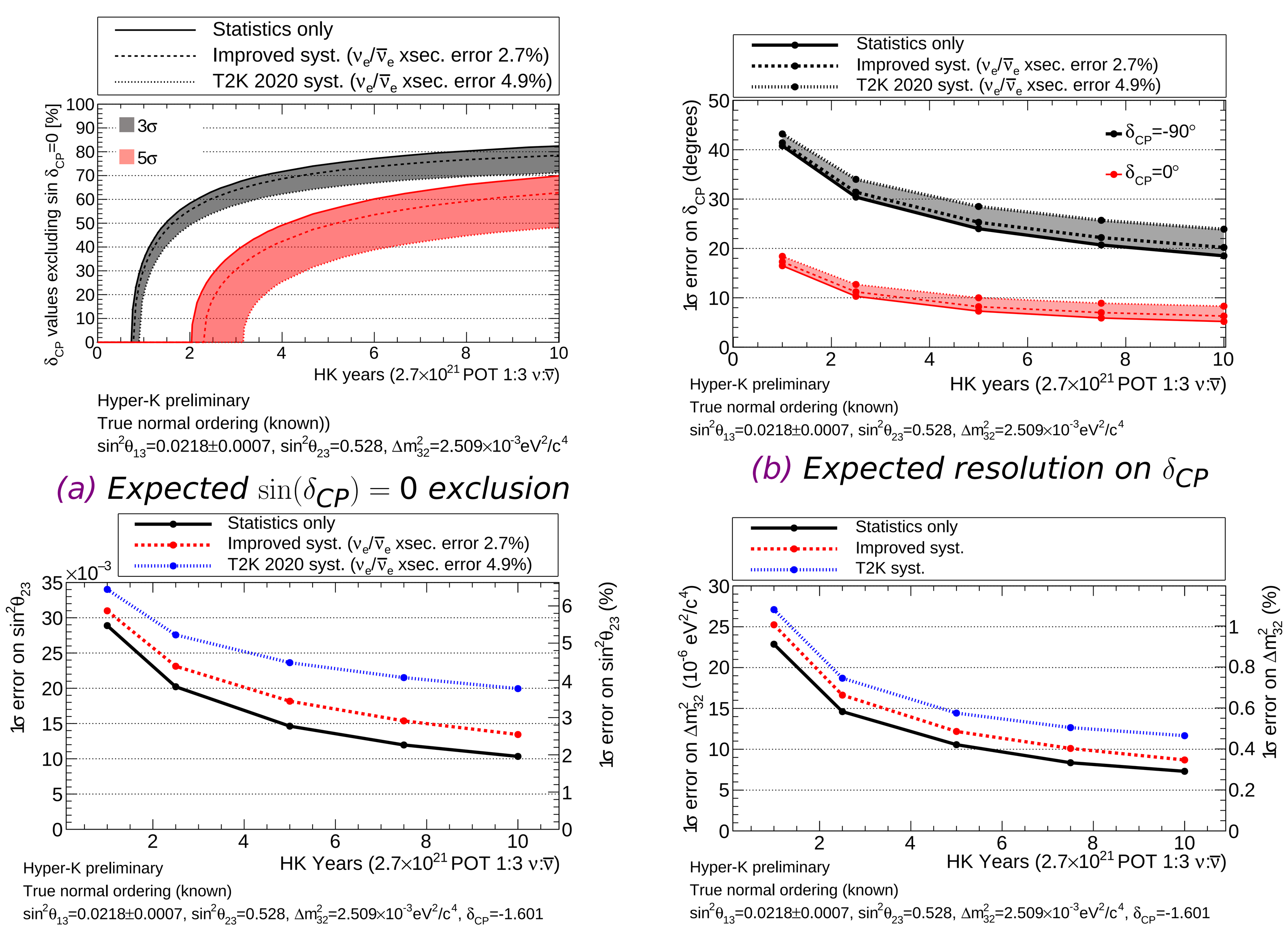
Figure 3. Current T2K flux uncertainties on the event rates in SK and impact of NA61/SHINE hadron production measurements with the T2K replica target.

Sensitivity studies for Hyper-Kamiokande

New sensitivity studies were performed in France (LPNHE+LLR/CEA) using the latest published T2K results [3].

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.

Developments towards Hyper-Kamiokande reconstruction

Hyper-Kamiokande event reconstruction is using the **fiTQun algorithm**, already employed in the last analysis of its predecesor Super-Kamiokande. It is based on the maximization of the likelihood

$$\mathcal{L}(\mathbf{X}) = \prod_{j}^{n_{\text{unhit}}} P_j(\text{unhit}|\mathbf{X}) \prod_{i}^{n_{\text{hit}}} (1 - P_i(\text{unhit}|\mathbf{X}))\ f_q(q_i|\mathbf{X})\ f_t(t_i|\mathbf{X})$$

for the (multi-)particle parameters $\mathbf{X}$, where $P(\text{unhit}|\mathbf{X})$, $f_q(q|\mathbf{X})$ and $f_t(t|\mathbf{X})$ represent the unhit, charge and time probabilities for a given hit. The different algorithm parameters are detector dependent and must be tuned based on **detector simulation and calibration**.

Current algorithm's implementation has been exclusively adjusted for Super-Kamiokande detector, lacking the **performance** requirements for larger Hyper-Kamiokande statistics, and must be adapted to the **multi-PMT technology**.

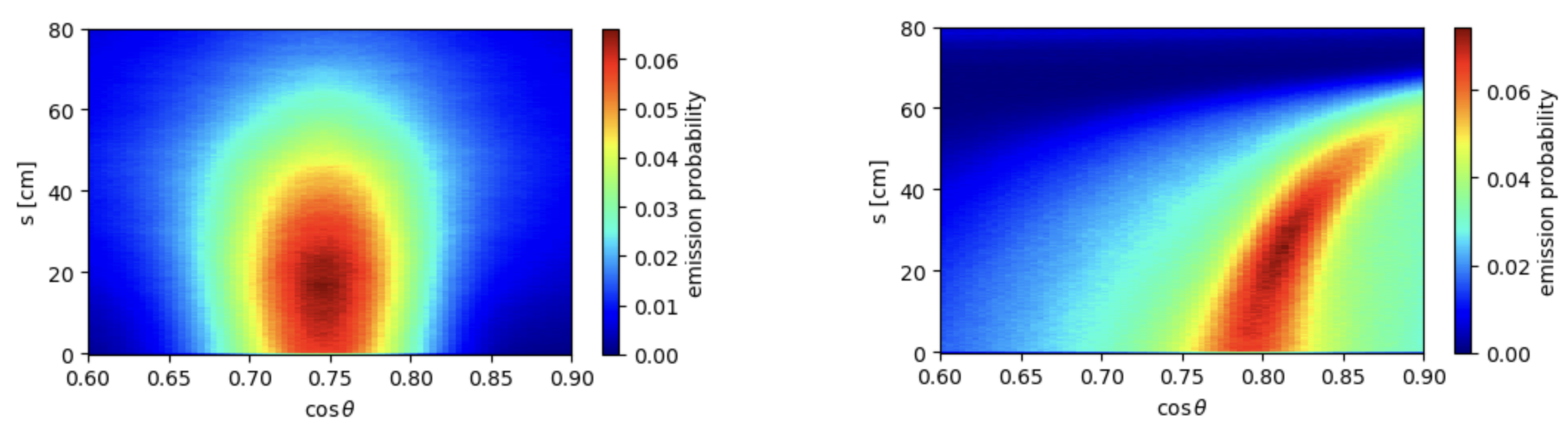
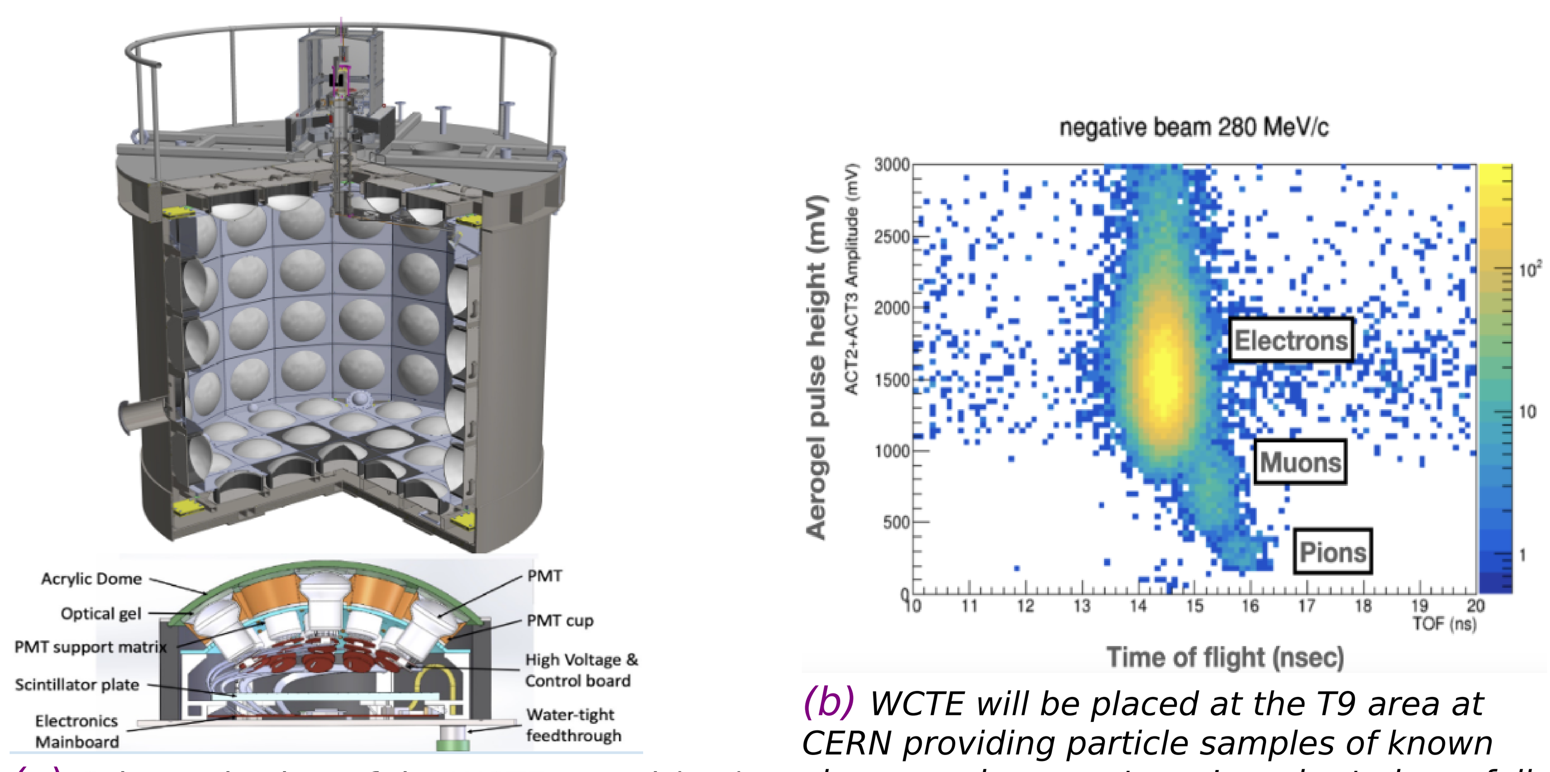


*Figure 5. **fiTQun** likelihood concept allows particle identification thanks to the different Cherenkov Profiles of the reconstructed particles. This plot shows the simulated profiles for electrons (left) and negatively charged muons (right) with a momentum of 300 MeV/c.*

This **new activity at LPNHE** is focussed on the preparation of the **fiTQun** reconstruction for Hyper-Kamiokande. For this purpose, we will tune the reconstruction for the **WCTE project** at CERN, whose objective is to develop calibration methods to control uncertainties in event reconstruction and energy scale to the 1% level.



(a) Schematic view of the WCTE vessel (top) and a multi-PMT module (bottom). The detector will consist of a tank of 3.8 m diameter and 3.5 m height, leading to a 40 ton tank filled with ultra pure water and instrumented with 102 multi-PMT modules with 19 PMTs each.

*(b) WCTE will be placed at the T9 area at CERN providing particle samples of known charge and momentum. In order to have full control over the primary interacting particles, an extra setup for particle identification has been tested during this summer (2023) with **LPNHE's** contribution.*

*Figure 6. The **WCTE project** will be a smaller detector test bench for the next generation water-Cherenkov experiments.*

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. DOI: https://doi.org/10.1140/epjc/s10052-023-11819-x.