From T2K to Hyper-Kamiokande

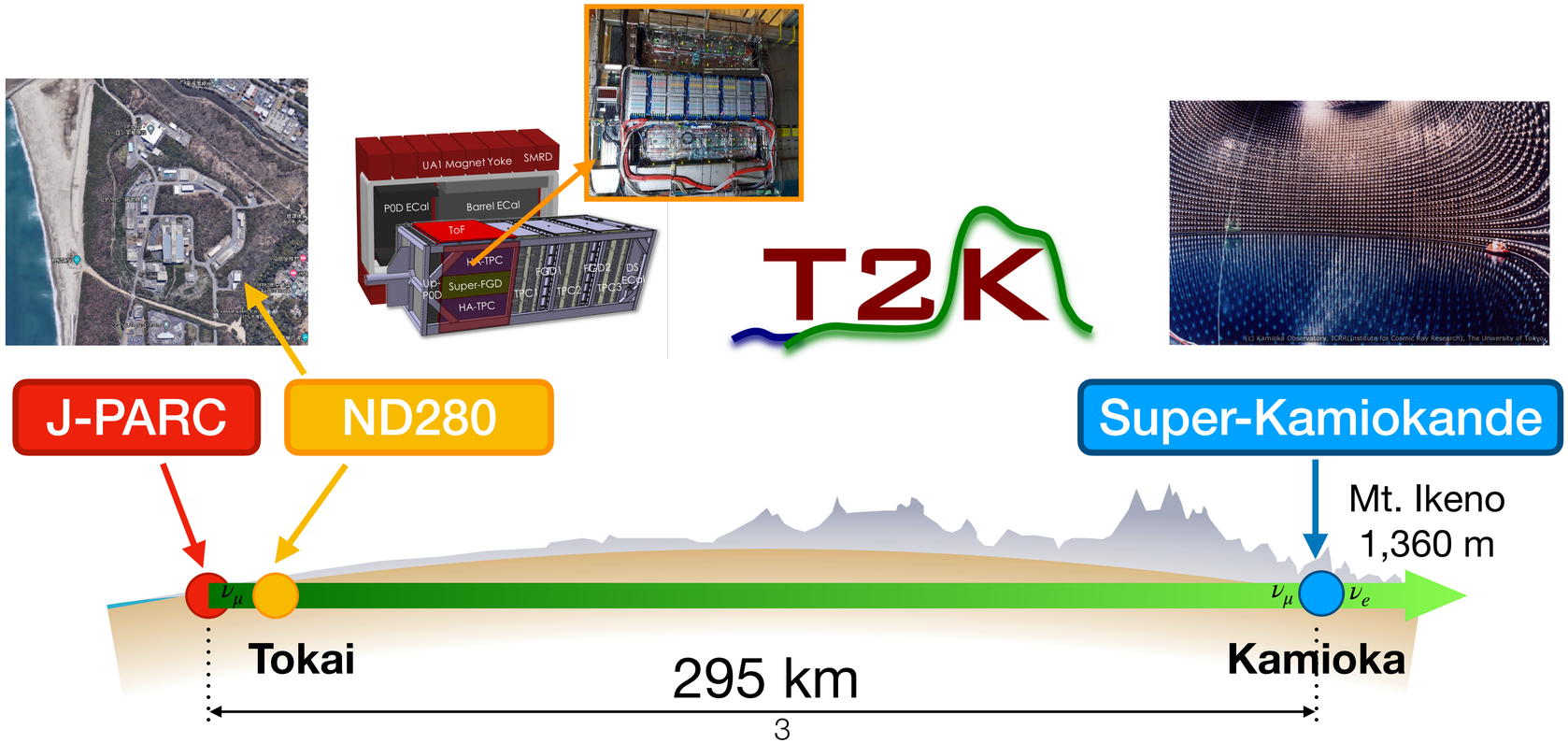
Claudio Giganti

The Japanese LBL programme

- Successful programme since > 20 years
- Based on the well established water Cherenkov technology for the far detector
  - First detection of SN neutrinos by Kamiokande (1987)
  - Discovery of neutrino oscillations by Super-Kamiokande (1998)
  - First observation of ν_μ disappearance (K2K in 2005) and ν_e appearance (T2K in 2013) in ν beam
  - Hints of CP violation in the leptonic sector by T2K in 2019
- Towards precision measurements
  - High stat with larger far detector → Hyper-Kamiokande will start in 2027
  - Small syst with near detectors → ND280 upgrade finalized in 2024, ND280++ for Hyper-Kamiokande?

T2K experiment

- High intensity ~600 MeV ν_μ or $\bar{\nu}_\mu$ beam produced at J-PARC (Tokai)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande)
  - ν_e and $\bar{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ disappearance → θ_{23} and $|\Delta m^2_{32}|$

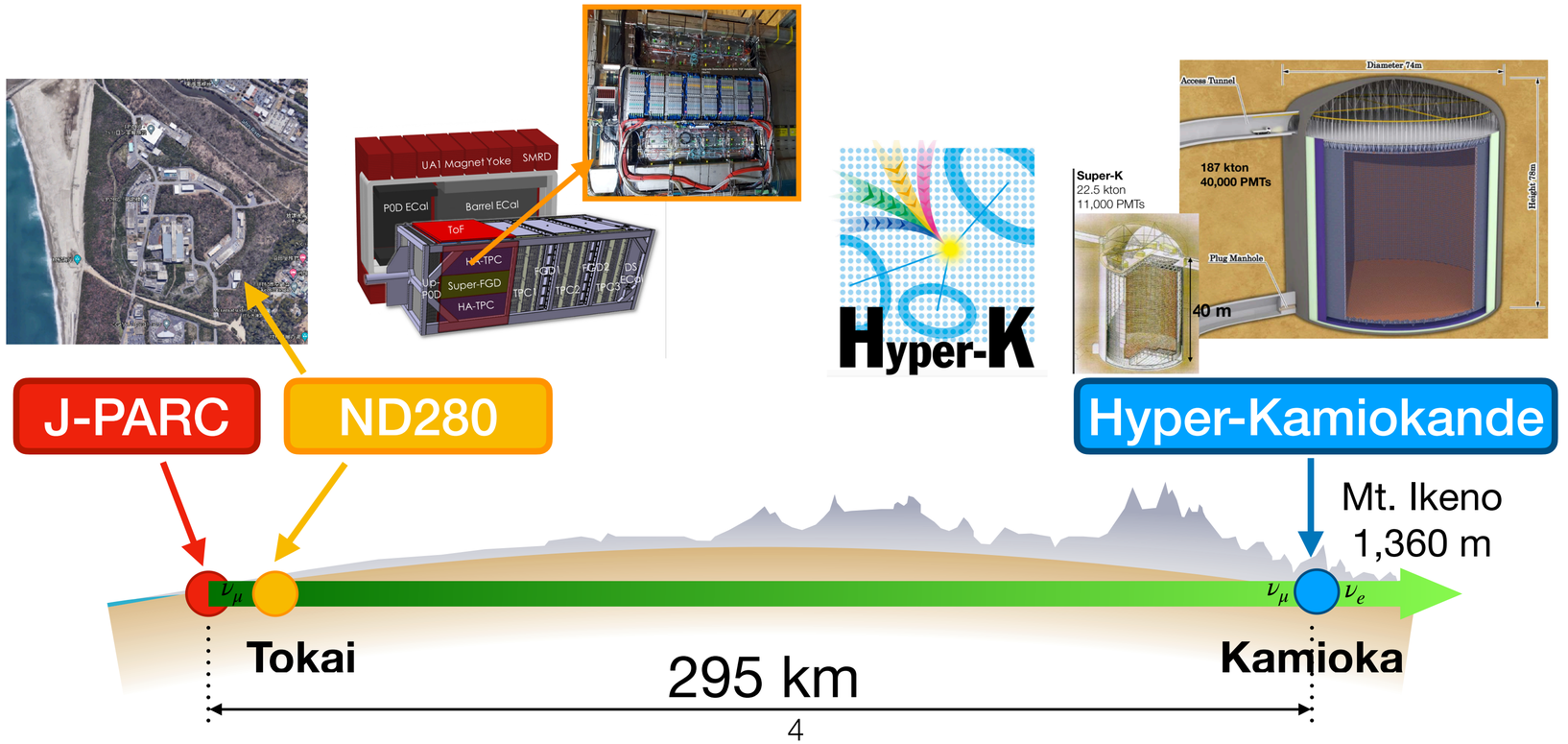


Hyper-Kamiokande

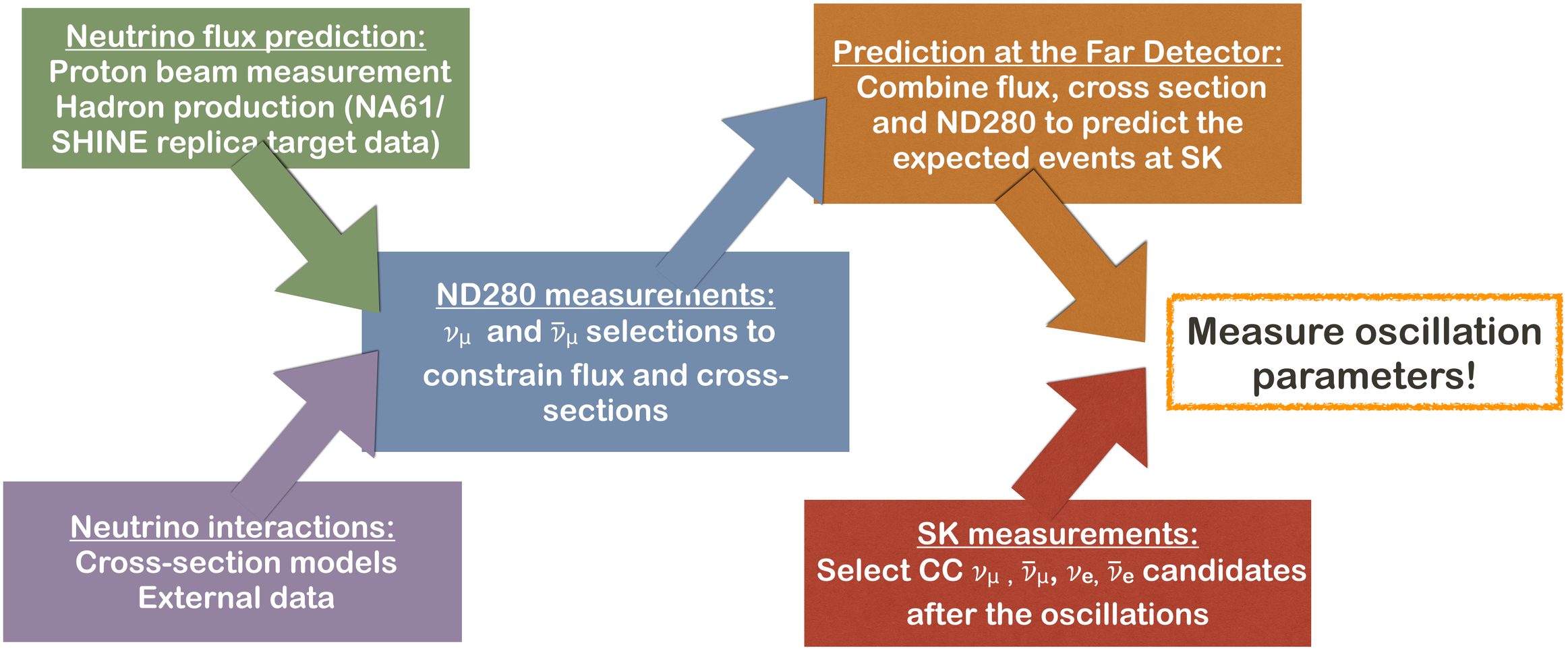
- Same beamline but higher intensity 500 kW → 1.3 MW
- From SK to HK → 8 times larger far detector

1 y HK ~ 20 y of T2K

- Huge stat from day 0 → need a well understood Near Detector to characterize beam → ND280
- Towards high precision → add intermediate detector (IWCD) and further upgrades of ND280 (ND280++)

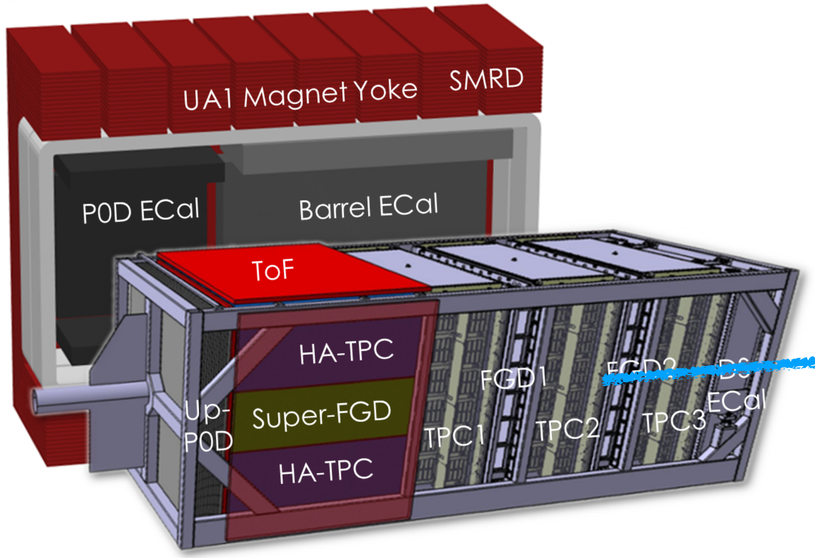


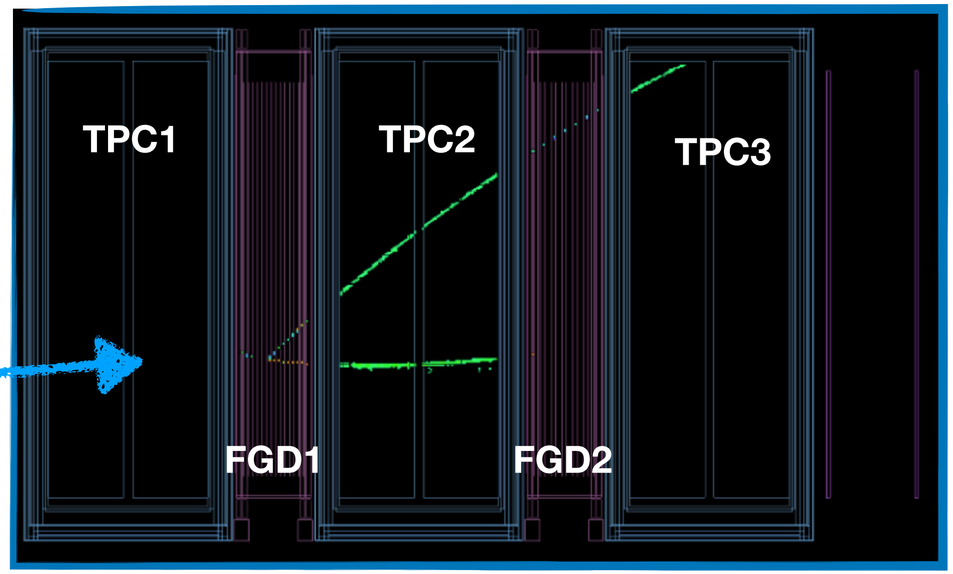
T2K/HK oscillation analysis



Near and Far detector data are fitted either sequentially or simultaneously depending on the analysis considered

Off-axis ND280

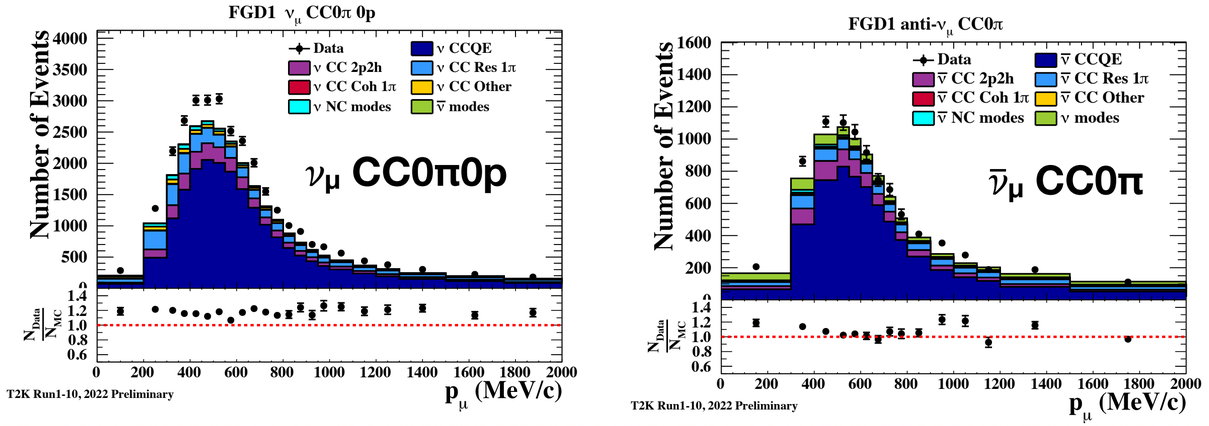




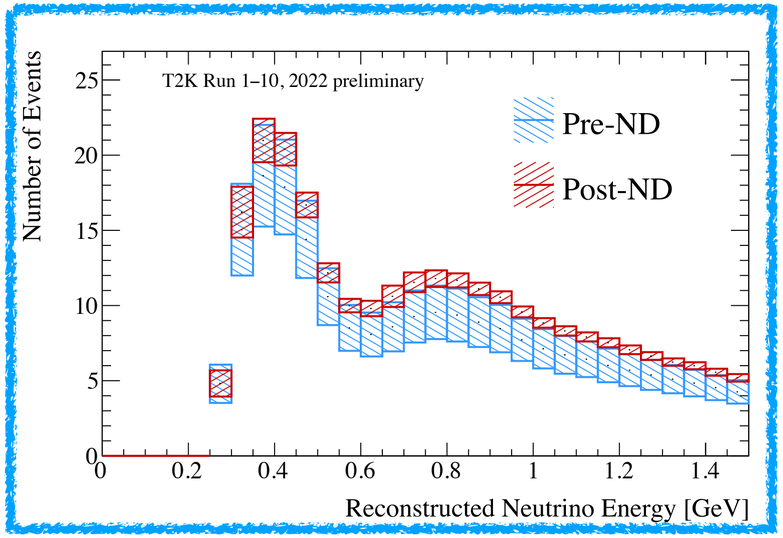
- Measure beam spectrum and flavor composition before the oscillations
- Detector installed inside the UA1/NOMAD magnet (0.2 T)
- An electromagnetic calorimeter to distinguish tracks from showers
- Upgraded in 2023 but for the analyses shown here the original tracker system is used:
  - 2 Fine Grained Detectors (target for ν interactions). FGD1 is pure scintillator, FGD2 has water layers interleaved with scintillator
  - 3 Time Projection Chambers: reconstruct momentum and charge of particles, PID based on measurement of ionization

Systematics uncertainties

Before the ND280 fit

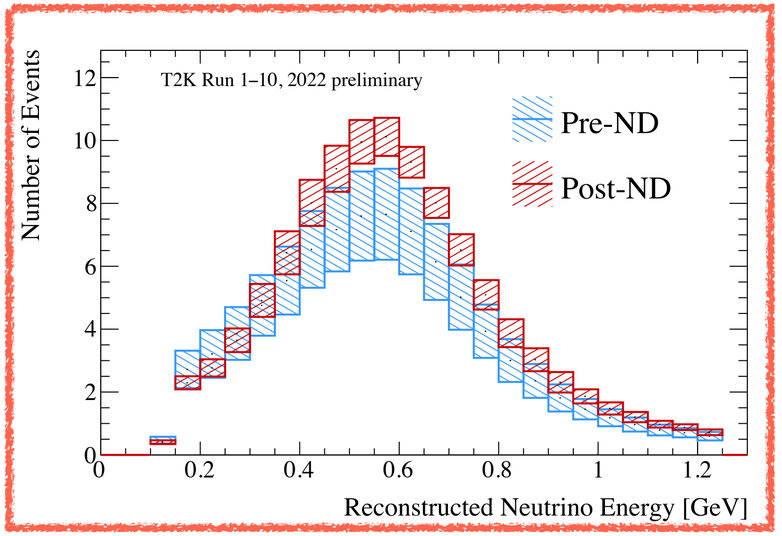


SK Single ring μ-like sample



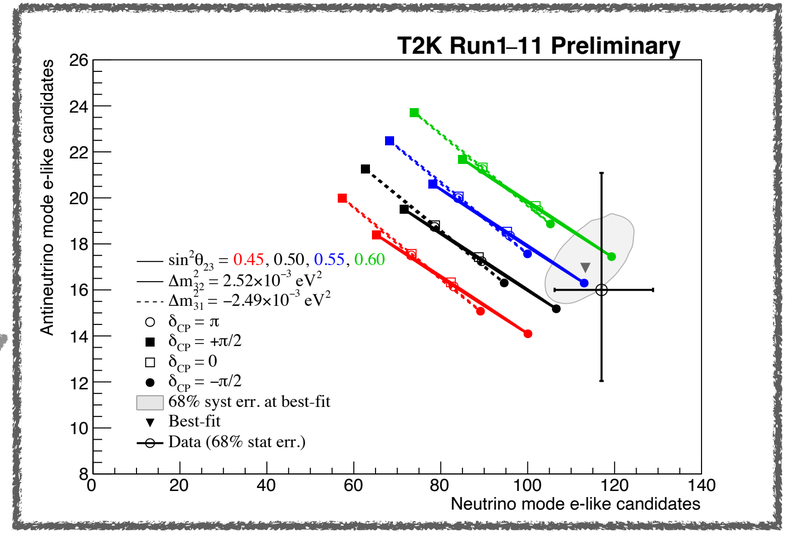
Sample	Pre-ND fit	Post-ND fit
ν-mode 1Rμ	16.7%	3.4%
ν-mode 1Re	17.3%	5.2%
ν-mode MR	12.5%	4.9%
ν-mode 1Re+d.e.	20.9%	14.3%
$\bar{\nu}$-mode 1Rμ	14.6%	3.9%
$\bar{\nu}$-mode 1Re	14.4%	5.8%

SK single ring e-like sample

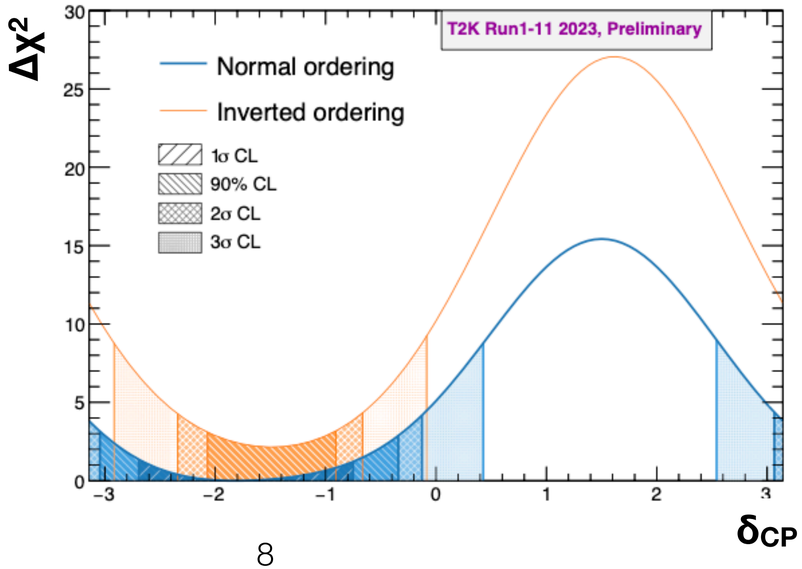


Oscillation analysis results

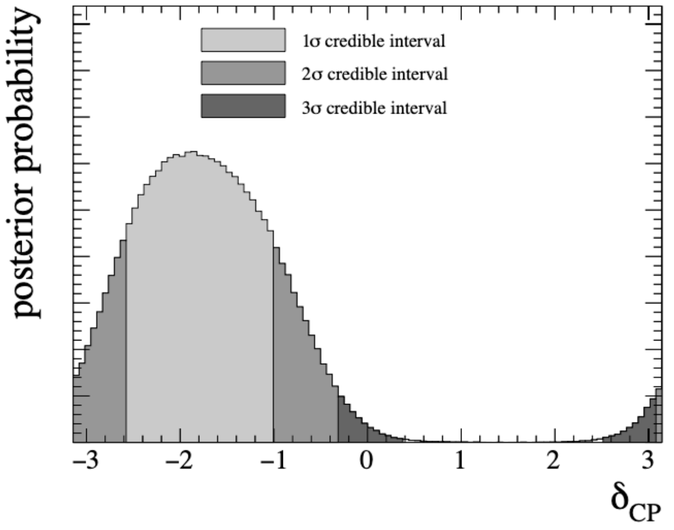
Sample	δ_{CP}=-π/2	δ_{CP}=0	δ_{CP}=π/2	δ_{CP}=π	Data
ν-mode 1Rμ	417.2	416.3	417.1	418.2	357
ν-mode MR	123.9	123.3	123.9	124.4	140
$\bar{\nu}$-mode 1Rμ	146.6	146.3	146.6	147.0	137
ν-mode 1Re	113.2	95.5	78.3	96.0	102
$\bar{\nu}$-mode 1Re+d.e.	10.0	8.8	7.2	8.4	15
$\bar{\nu}$-mode 1Re	17.6	20.0	22.2	19.7	16



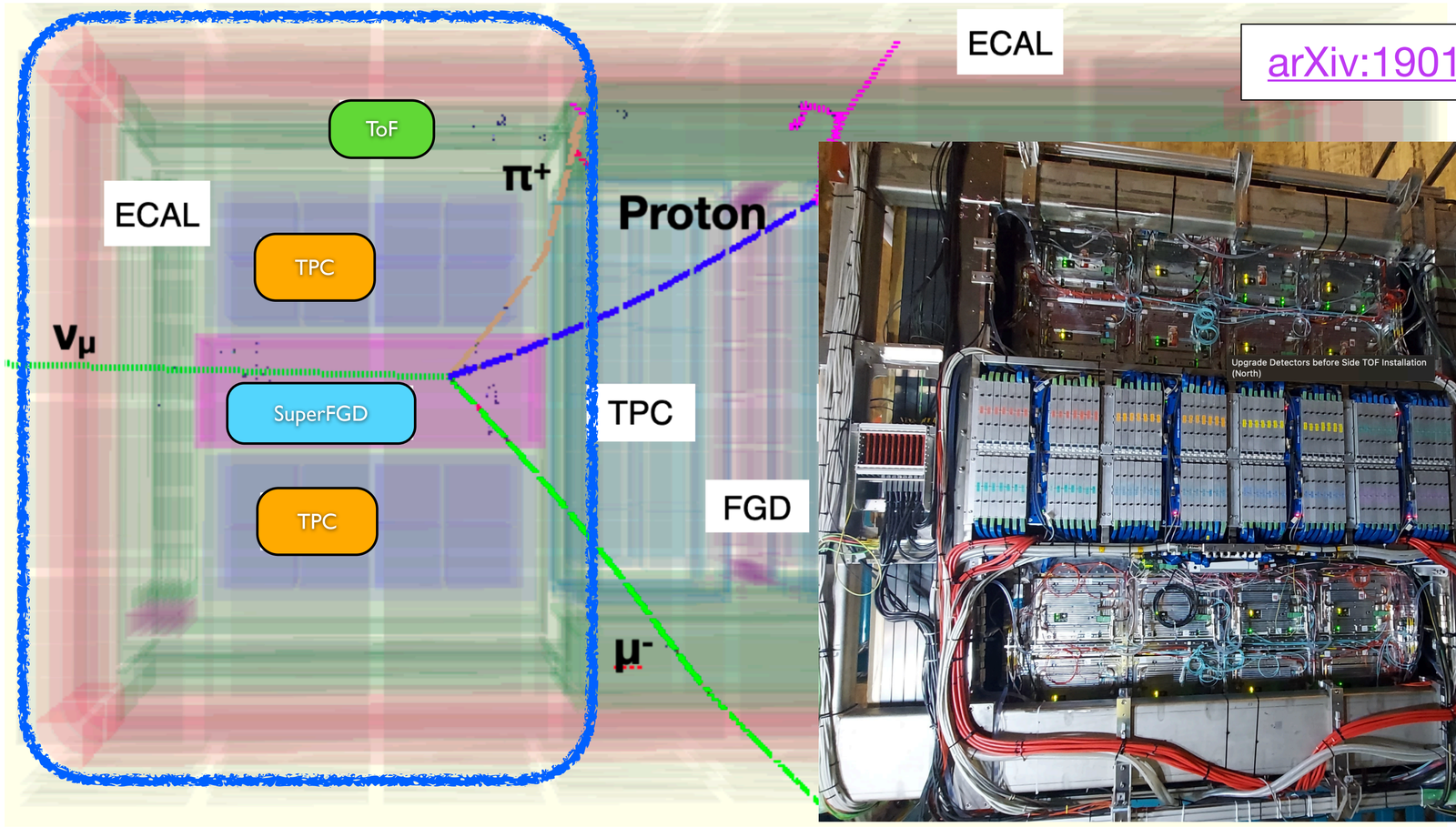
- Preference for δ_{CP}~-π/2 but CP conserving values are within the 2σ interval



Credible intervals marginalized over both hierarchies



The Near Detector upgrade



arXiv:1901.03750

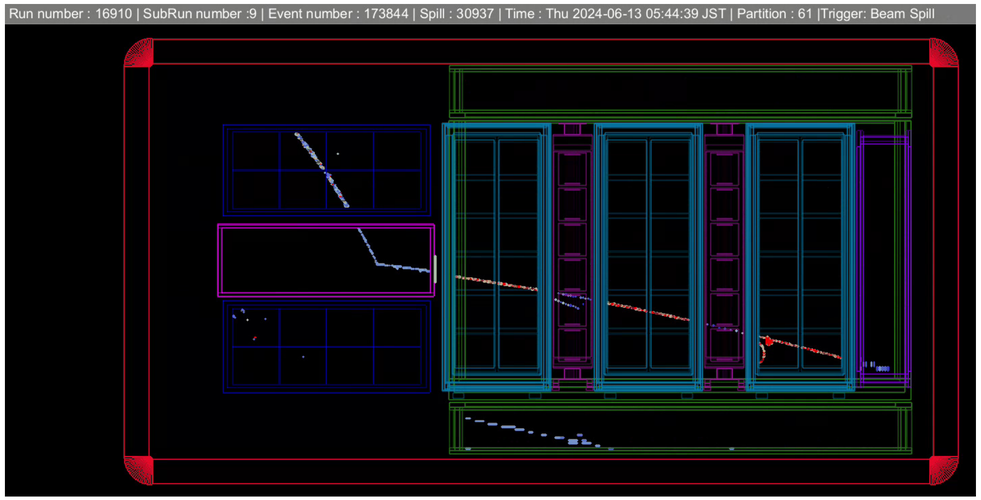
Strong contribution from CERN and Neutrino Platform

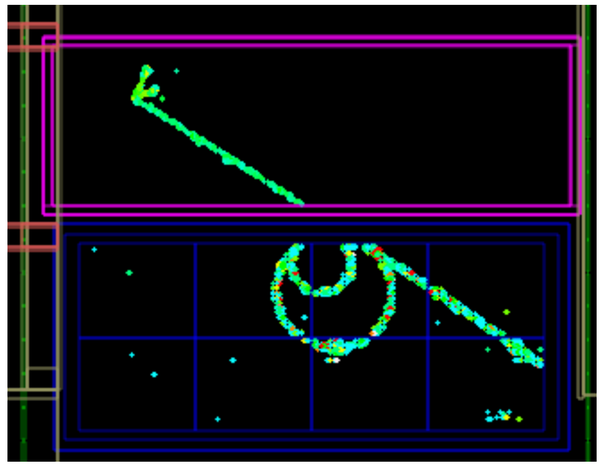
NP-07 project

- **Assembly of the two High-Angle TPCs and of the 6 TOF planes at CERN**
- **Production of ERAM readout planes**
- **TPC gas system done by CERN**
- **Procurement and shipment of Super-FGD box**
- **CERN EP NU group working on T2K**

Replace part of the P0D detector (measured NC π^0 production) with a new scintillator target (SuperFGD), two High-Angle TPCs and six ToF planes

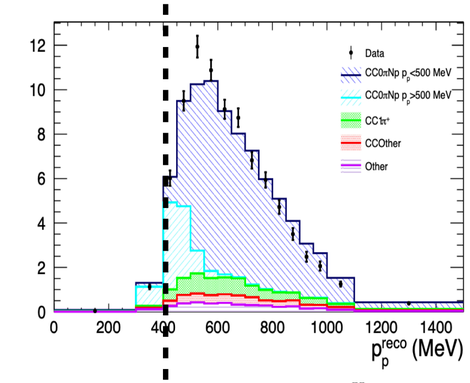
From T2K to HK

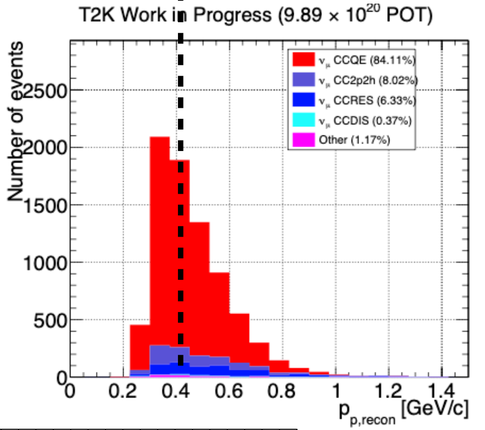




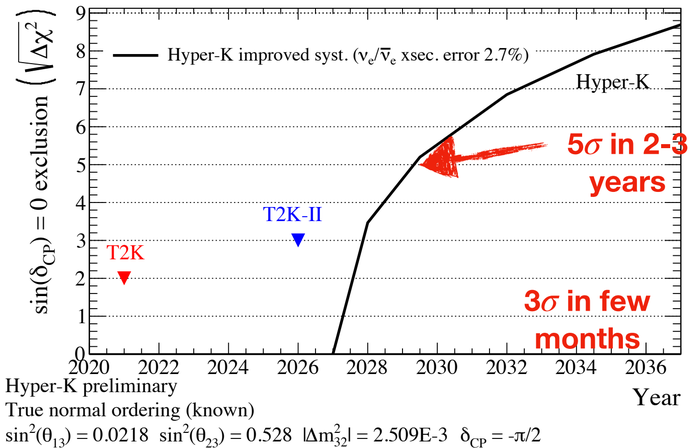
FGD

sFGD



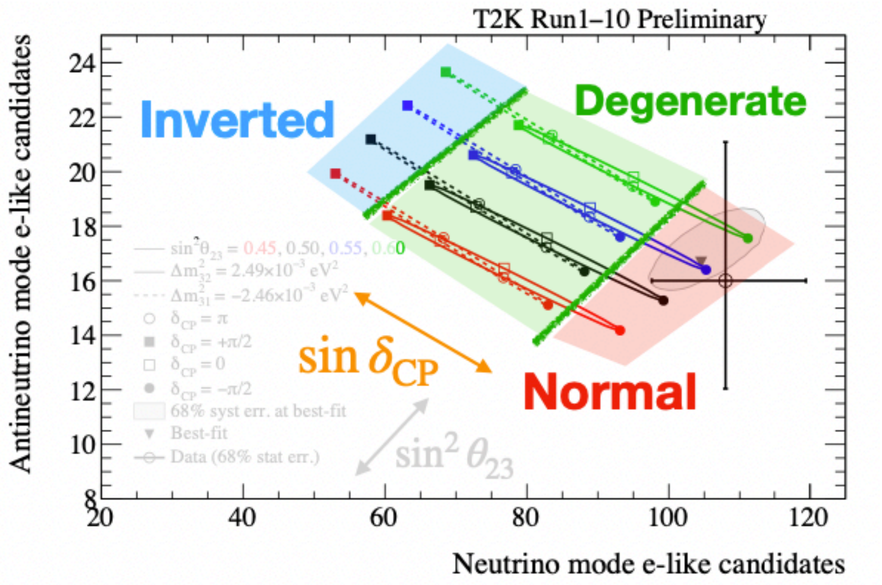


- First physics runs with full ND280 upgrade on-going
- Expect to select 20k ν_μ CC0π interactions in the super-FGD for 1 month of beam
  - ~ half of them with a reconstructed proton
- Reduce systematics uncertainties in T2K oscillation and cross-section analyses
- Ready to constraint flux and cross-section from day-0 of Hyper-Kamiokande
- Transfer French leadership in ND280 from T2K to HK
- Further ND280 upgrades ? ND280++!

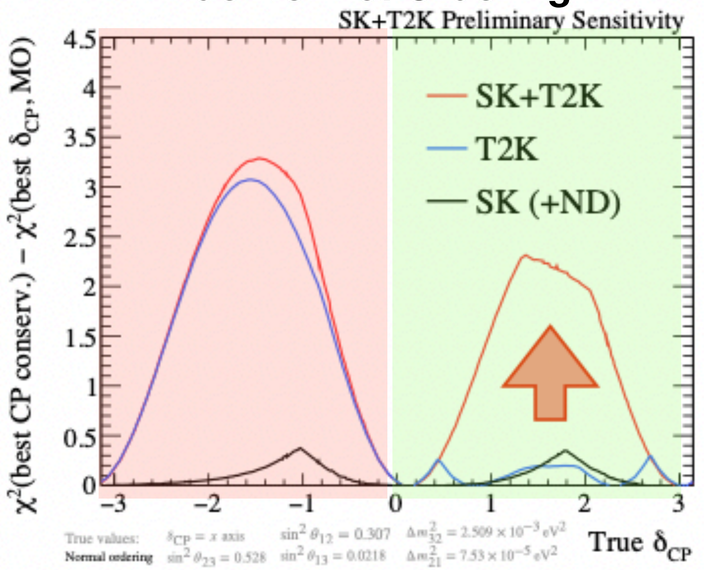


T2K+SK joint analysis

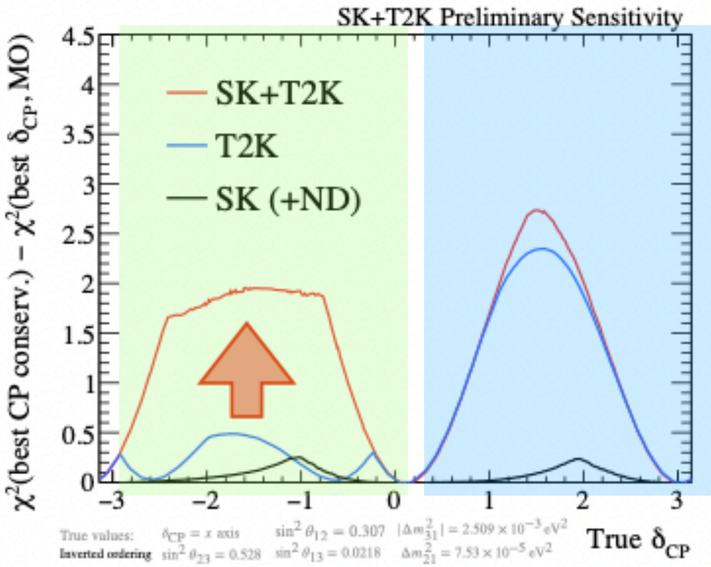
- T2K has good sensitivity to δ_{CP} but mild sensitivity to mass ordering
- SK has good constraint on mass ordering but not on δ_{CP}
- Adding SK atmospheric sample allows to break the degeneracies between the CP violation parameter δ_{CP} and the mass ordering → boost sensitivity to CP
- Proof of concept for Hyper-Kamiokande determination of mass ordering and δ_{CP}



True Normal Ordering

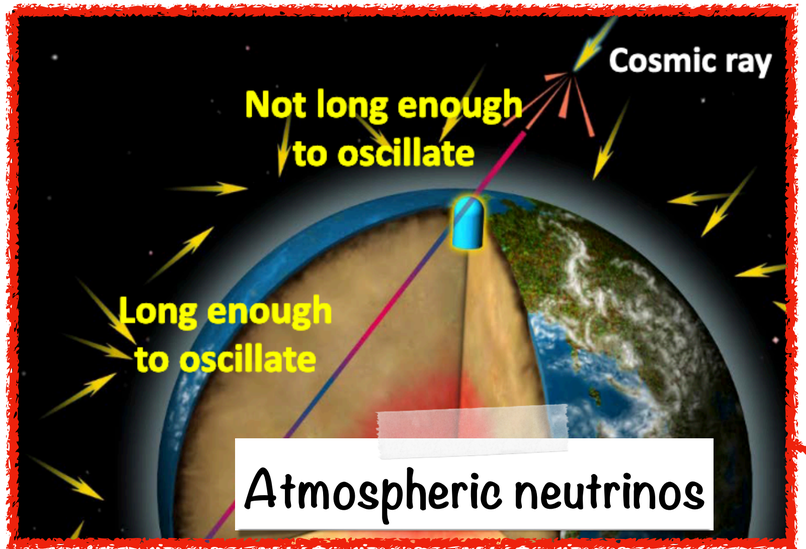


True Inverted Ordering

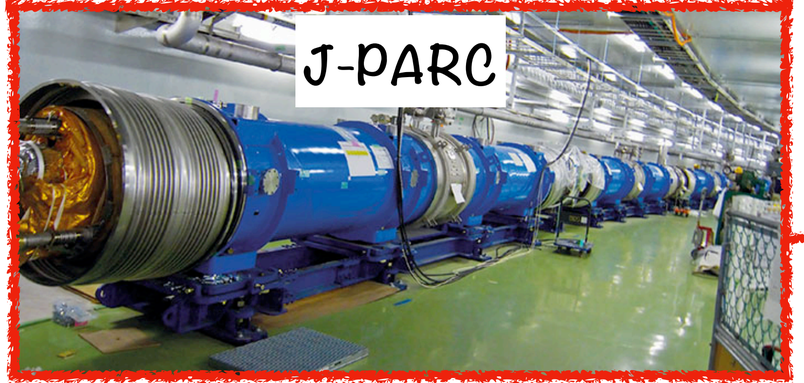


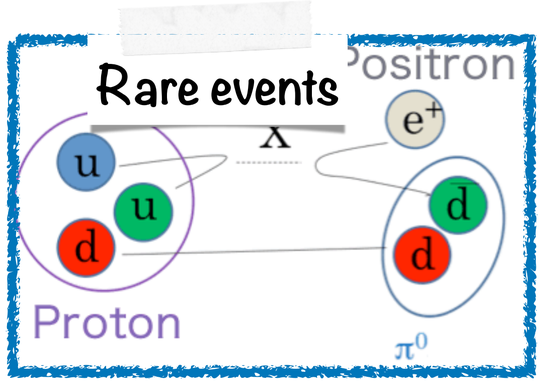
Hyper-Kamiokande

More details in Denis presentation tomorrow



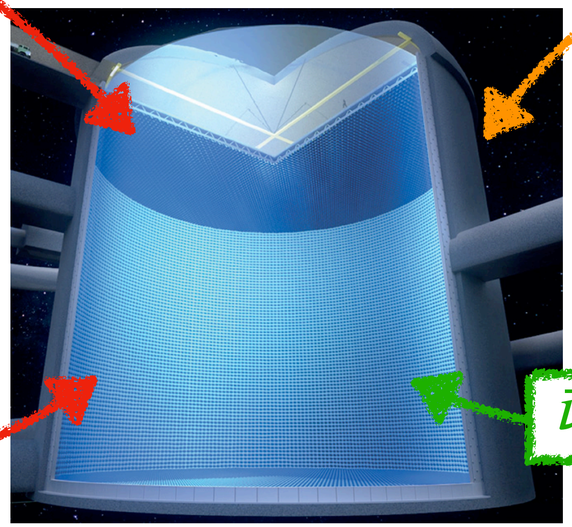
- Discovery of CP violation in the leptonic sector
- Precise measurement of δ_{CP}
- Sensitivity to mass ordering with atmospheric neutrinos





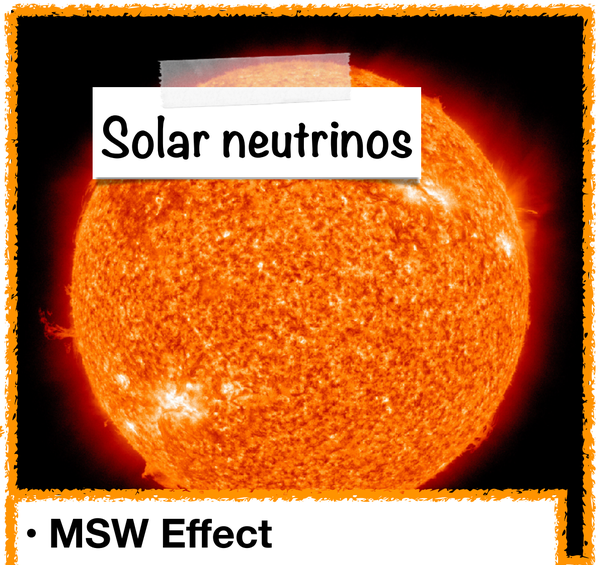
- Search for proton decay

ν_e ν_e
ν_μ $\bar{\nu}_\mu$

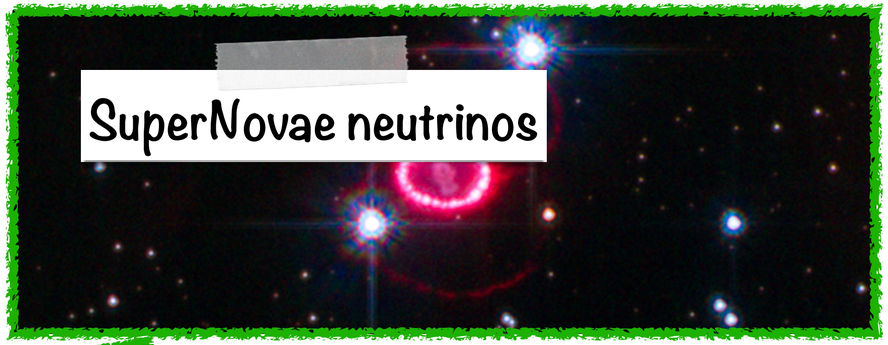


ν_e ν_e
ν_μ $\bar{\nu}_\mu$

ν_e



- MSW Effect
- Non standard interactions

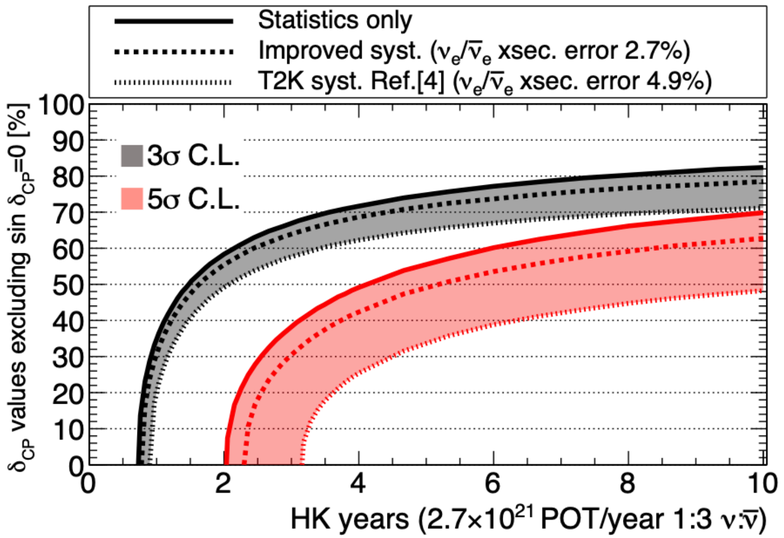


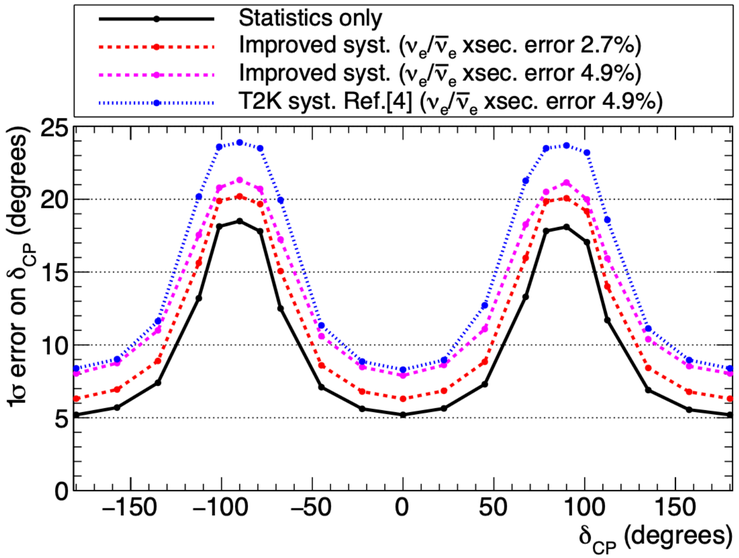
$\bar{\nu}_e$

- <u>SN ν transient:</u> explosion models
- <u>Relic SN:</u> star structure formation

HK sensitivity

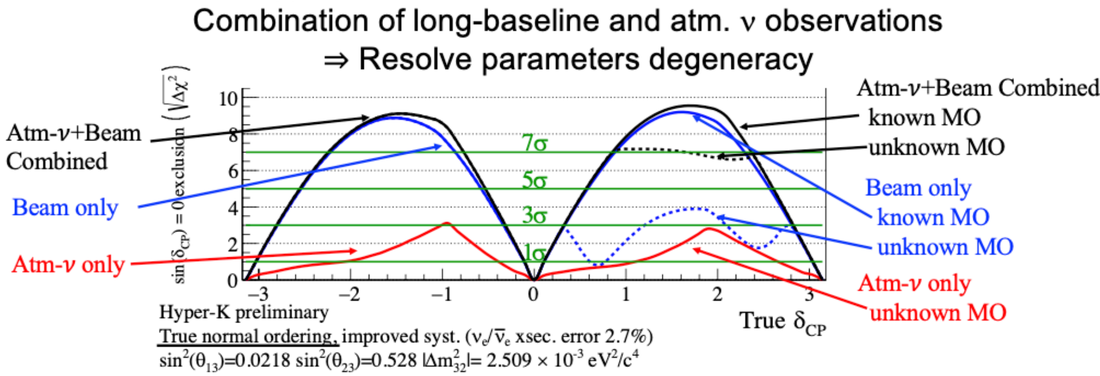
- Discovery of CP violation at 5σ (3σ) for >60% (>80%) of the possible values of δCP
  - For maximal CP violation 5σ discovery can be obtained in <3y
- Combination of beam and atmospheric neutrinos allows to resolve degeneracy between MO and δ_{CP}
- Sensitivity studies using T2K/SK joint analysis framework ongoing





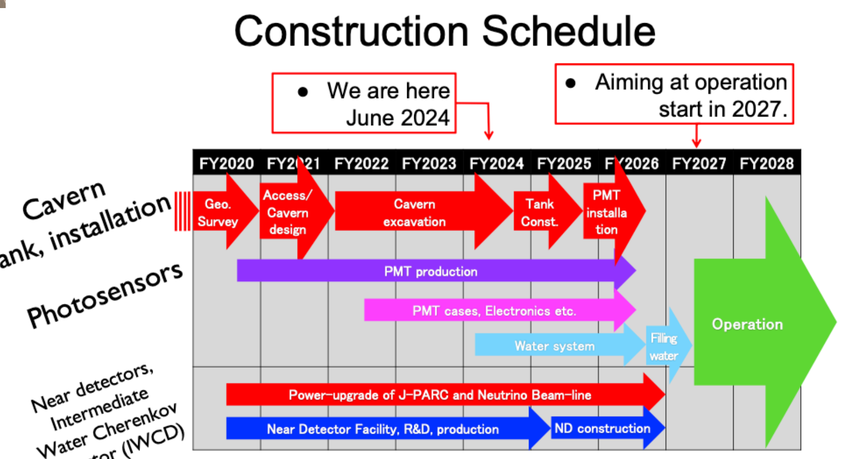
	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ	→ 3.8 σ
	0.60	4.9 σ	→ 6.2 σ
θ_{23} octant	0.45	2.2 σ	→ 6.2 σ
	0.55	1.6 σ	→ 3.6 σ

10 years with 1.3MW, normal mass ordering is assumed



HK construction status

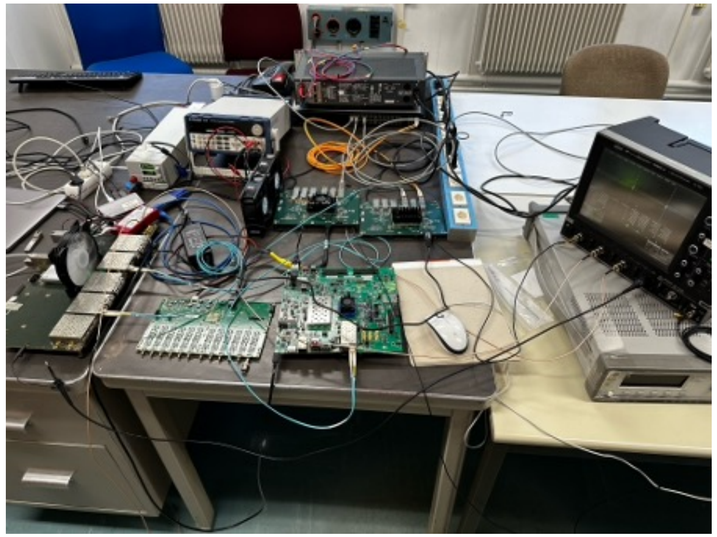
Excavating world largest human-made cavern

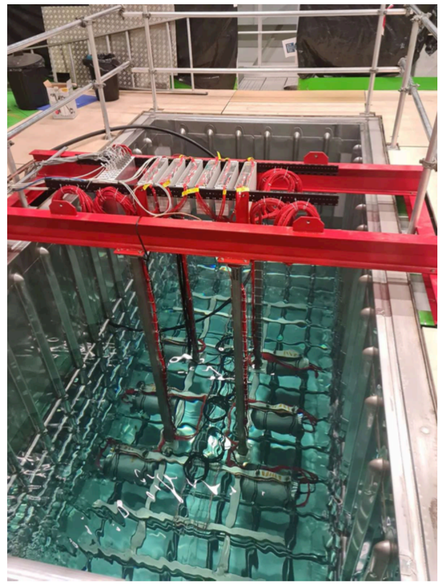


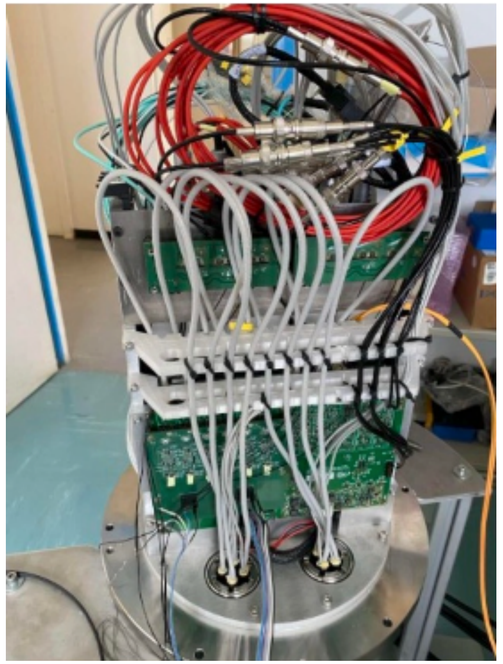
- Excavation on-going → expect to complete by the end of the year
- 20” PMTs being produced by Hamamatsu
- Assembly of the electronics modules on-going at CERN (next slide)
- Goal to start HK operation in 2027

HK activities at CERN

- HK electronics mostly produced in Europe
- In France we are responsible for the time generation and distribution system and for the test bench @ CERN
- All modules (~1000) will be assembled at CERN in 2025 before shipment to Kamioka
- Currently working on the 10-units test iand on the vertical slice tests with the purpose of testing all the subsystem before mass production
- MoU to become a Neutrino Platform project in preparation







Conclusions

- Seamless program → world leading data taken by T2K while HK is being built
  - T2K data with upgraded Near Detector are critical for T2K but also for early analyses of Hyper-Kamiokande data
  - HK will come online in 2027 → 1 year of HK data ~ 20 years of T2K data
- Strong french contribution to this program from CEA and IN2P3 groups (LLR, LPNHE and ILANCE)
- Important roles of European groups in T2K and HK
- CERN has already been an hub for T2K/HK activities
  - NP-07 - T2K Near Detector upgrade
  - HK electronics assembly project
- Continuous support from Europe (and from CERN)