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

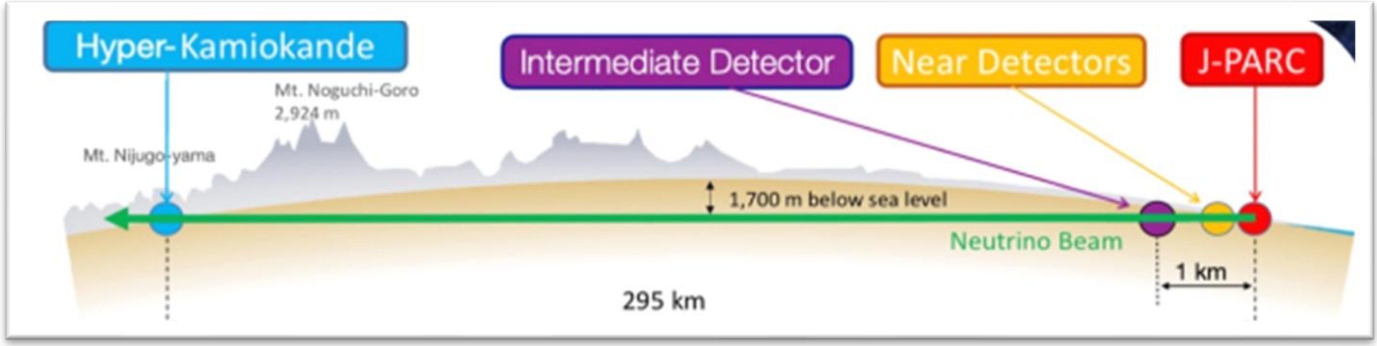
Romain Gaïor on behalf of the NU_09 project
2026/05/19

LPNHE
PARIS
ILANCE

Context of NU_09:

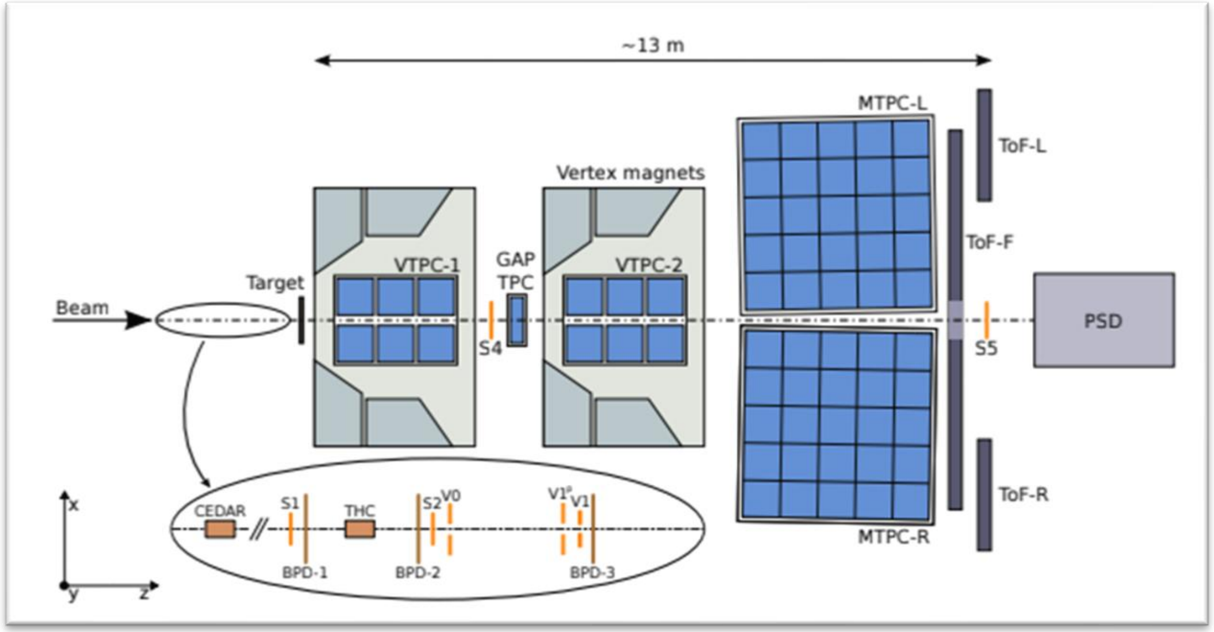
Motivation:

- ν oscillation with long baseline
- Broad ν physics program
- Search for CP violation



Tools

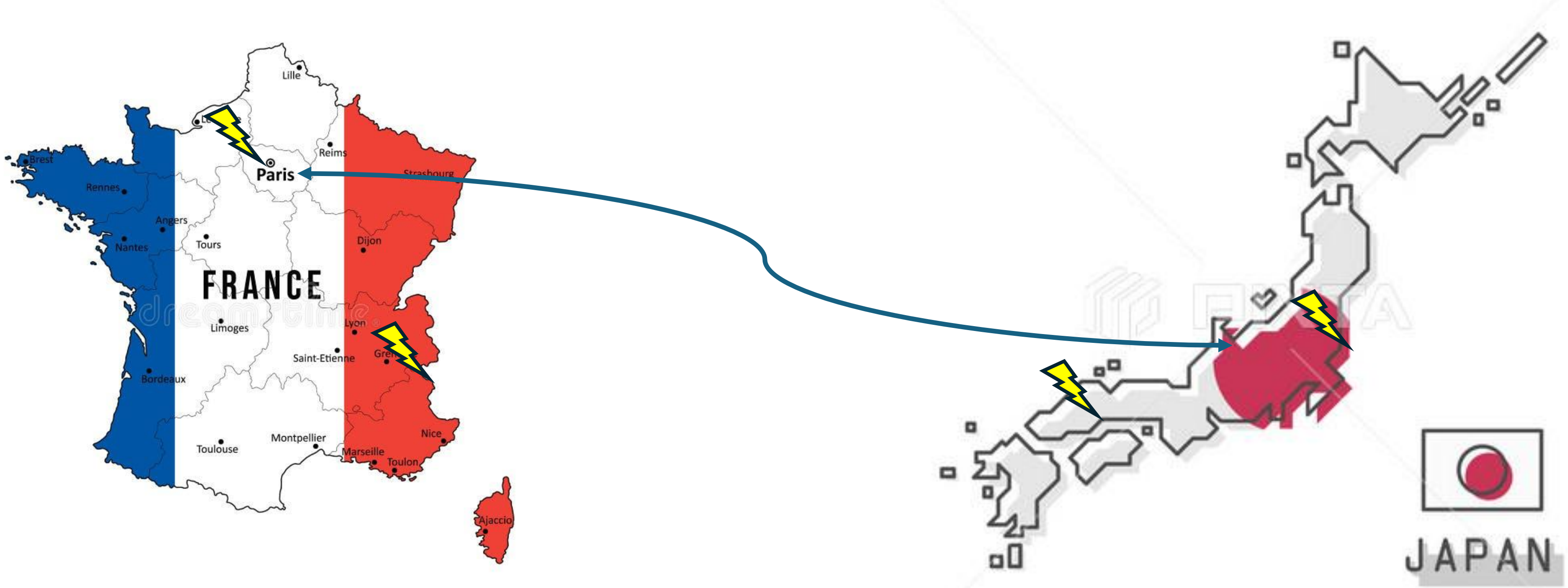
- T2(H)K
  - Beam from JPARC
  - Near Detector
  - Far Detector (Super / Hyper Kamiokande)
- NA61/SHINE
  - CERN based experiment to study the beam condition of T2K



Goal specific to NU-09:

- Improve the beam condition
- Characterize the beam
- Prepare future

France-Japan collaboration



LPNHE / CERN

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- Claire DALMAZZONE

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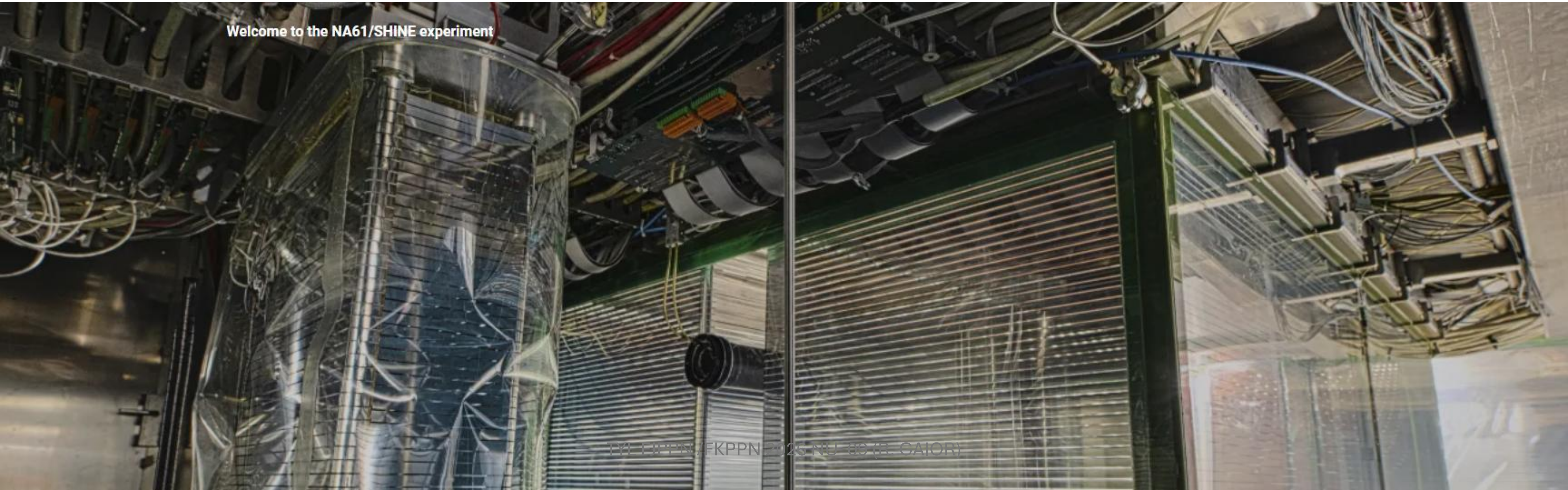
- Ayana ASAI
- Yuki SHIRAISHI
- Takeshi NAKADAIRA
- Sakiko NISHIMORI

Hadron flux estimation with NA61/SHINE



History of the data-taking for T2K

C target + proton@31 GeV/c run

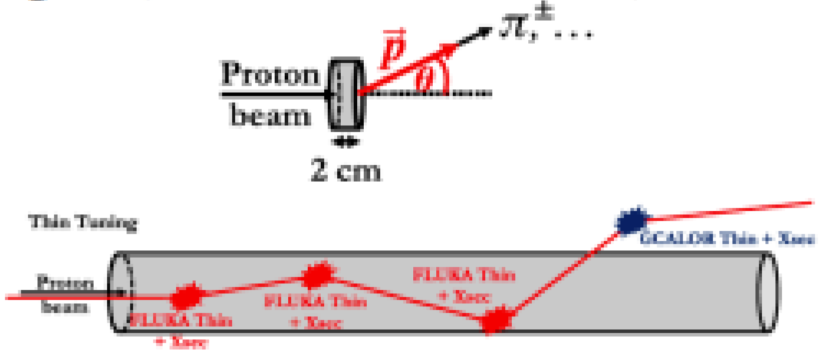
	2007年	2009年	2010年		2022年
Thin:	0.7×10^6 POT	5.4×10^6 POT	-	18 times	-
Replica:	0.2×10^6 POT	2.8×10^6 POT	$10. \times 10^6$ POT	→	$180. \times 10^6$ POT

<Thin target> (in use: 2009 data set)

NA61

↓

T2K



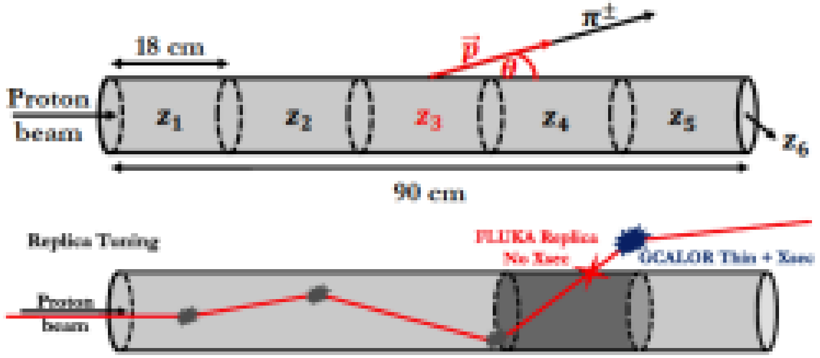
- Target length: 2 cm
- Measured value: $d^2\sigma/dp d\theta$
- The double differential production cross section is measured from the primary interactions.

<T2K replica target> (in use: 2010 data set)

NA61

↓

T2K



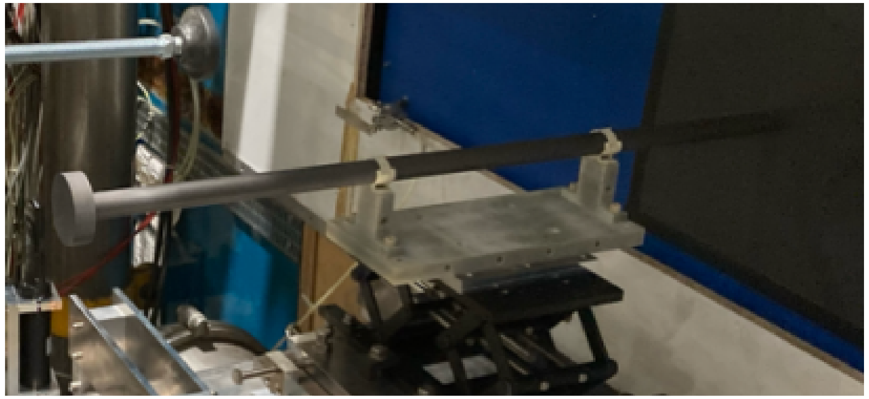
- Target length: 90 cm (the same as T2K)
- Measured value: $d^3N/dz dp d\theta$
- The hadron yields at the target surface are measured, and they can be used for the yield tuning directly.

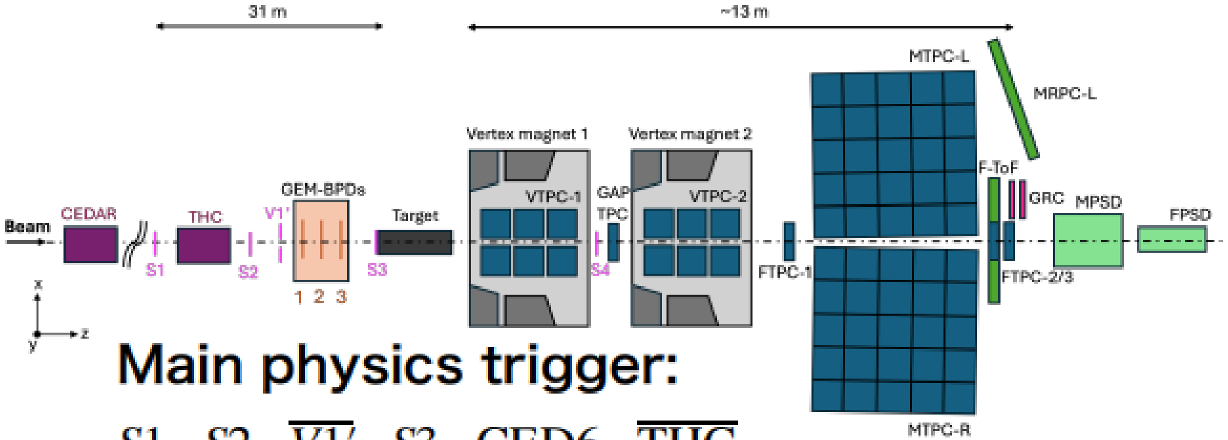
Slide from S. Nishimori

T2K replica target + proton@31 GeV/c run (2022)

	2007年	2009年	2010年		2022年
Thin:	0.7×10^6 POT	5.4×10^6 POT	-	18 times	-
Replica:	0.2×10^6 POT	2.8×10^6 POT	$10. \times 10^6$ POT	→	$180. \times 10^6$ POT

T2K replica target





Main physics trigger:

$$S1 \cdot S2 \cdot \overline{V1'} \cdot S3 \cdot \mathrm{CED6} \cdot \overline{\mathrm{THC}}$$

Particle	Thin (2 cm)	Replica (90 cm)	Plan with 2022 dataset
π^+/π^-	✅ (2009)	✅ (2010)	
K^+/K^-	✅ (2009)	△ (not enough)	Measurement of the high energy charged kaons
p	✅ (2009)	✅ (2010)	
K_S^0	✅ (2009)	❌	First measurements using a T2K replica target
Λ	✅ (2009)	❌	

- NA61/SHINE measures the differential production yield for each momentum and angle of K_S^0.
- The results are input to a T2K beam simulation to estimate K_L^0 production at T2K.
- The analysis in NA61/SHINE is performed by reconstructing the trajectory for the process of $K_S^0 \to \pi^+ + \pi^-$.

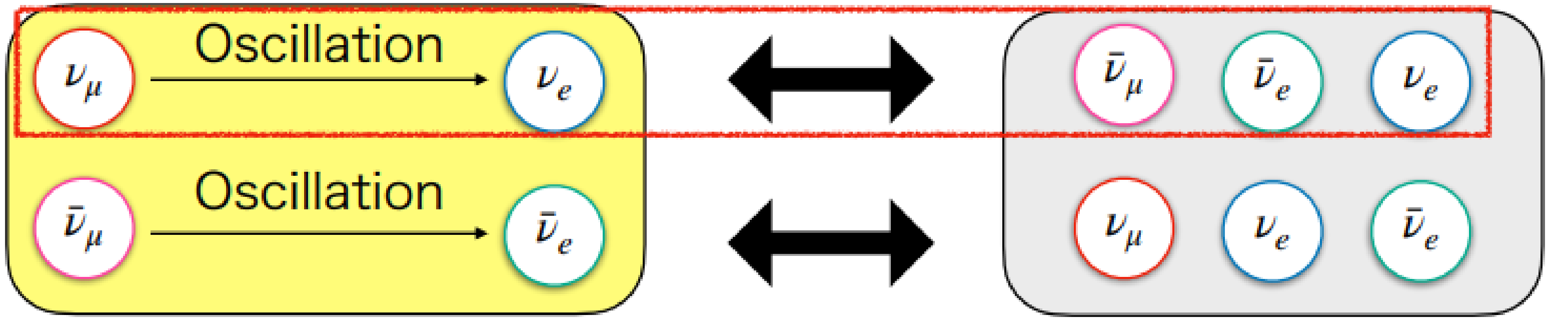
Slide from S. Nishimori

The motivation of K_S^0 measurement (1)

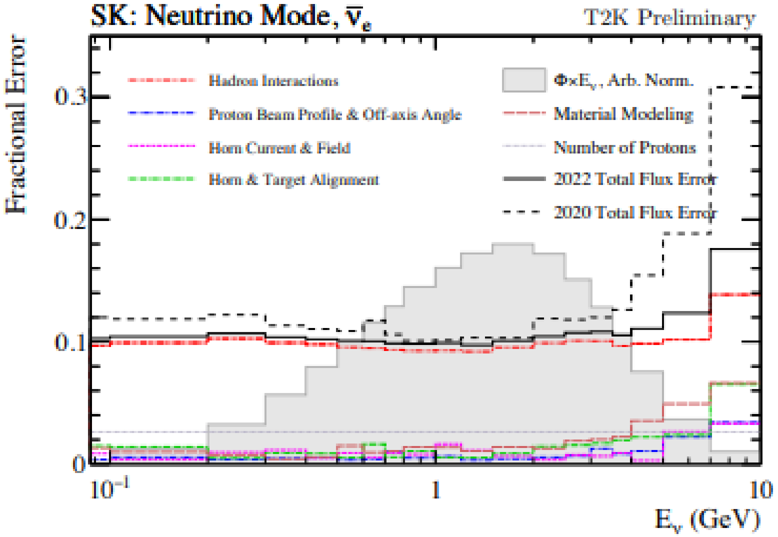
Background neutrinos
From the beam

Neutrino mode

Anti-neutrino mode



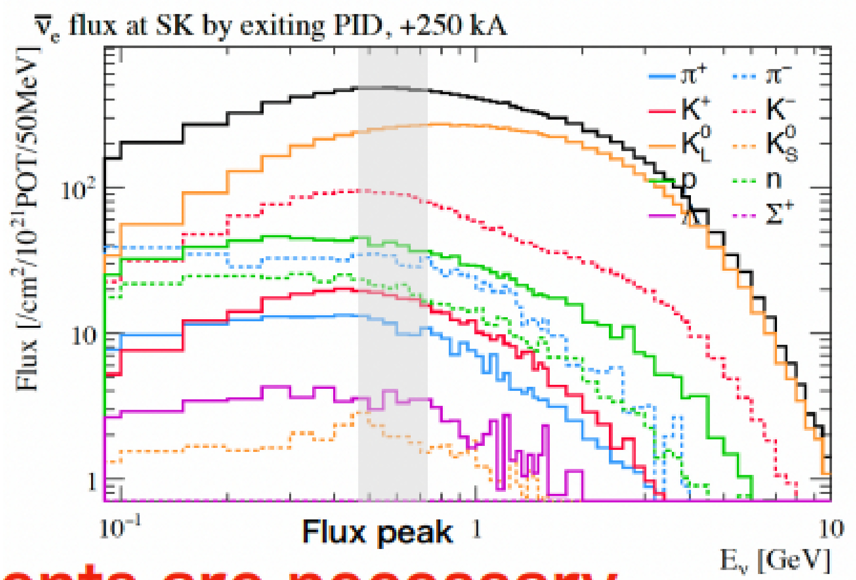
$\bar{\nu}_e$ **flux uncertainties at SK**



Main component

$$K_L^0 \rightarrow \pi^+ + e^- + \bar{\nu}_e$$

<$\bar{\nu}_e$ flux by type of parent particle (Neutrino mode)>

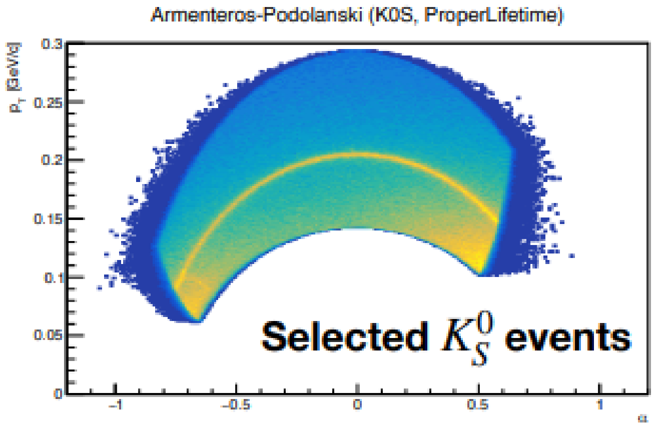


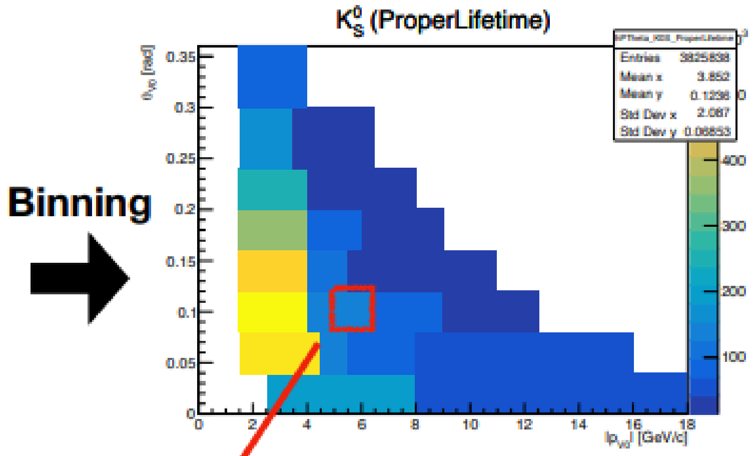
Additional NA61/SHINE measurements are necessary.

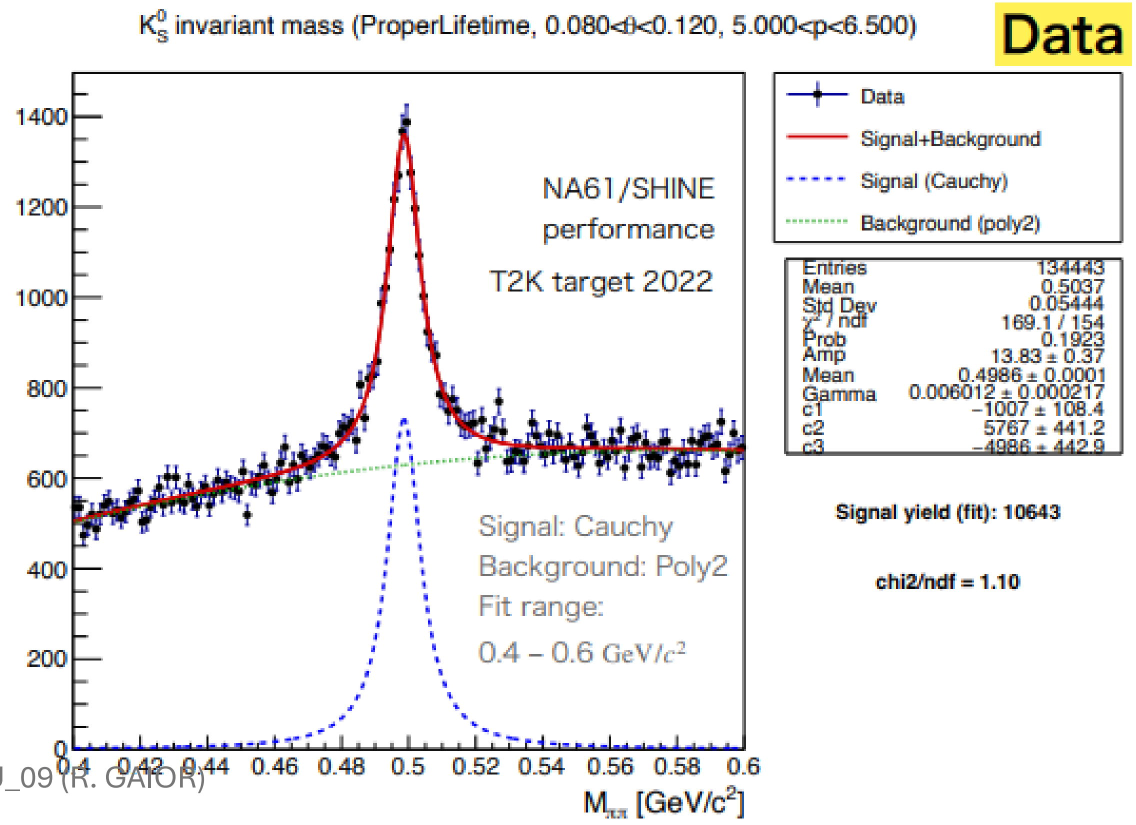
Slide from S. Nishimori

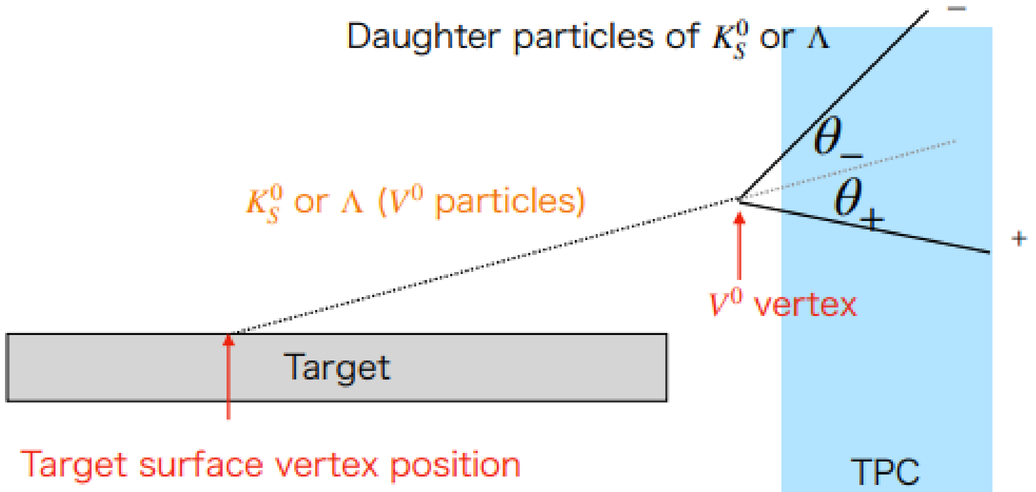
K_S^0 analysis status

- The data analysis is currently under review within the NA61 collaboration, and results will be published soon.
- Invariant mass fits are performed well for each kinematic bin.







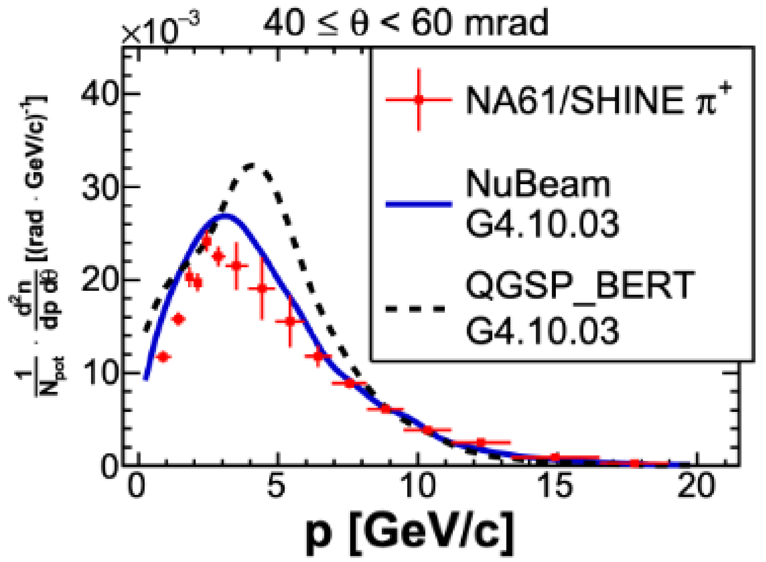


Slide from S. Nishimori

Beam operation and characterization at JPARC

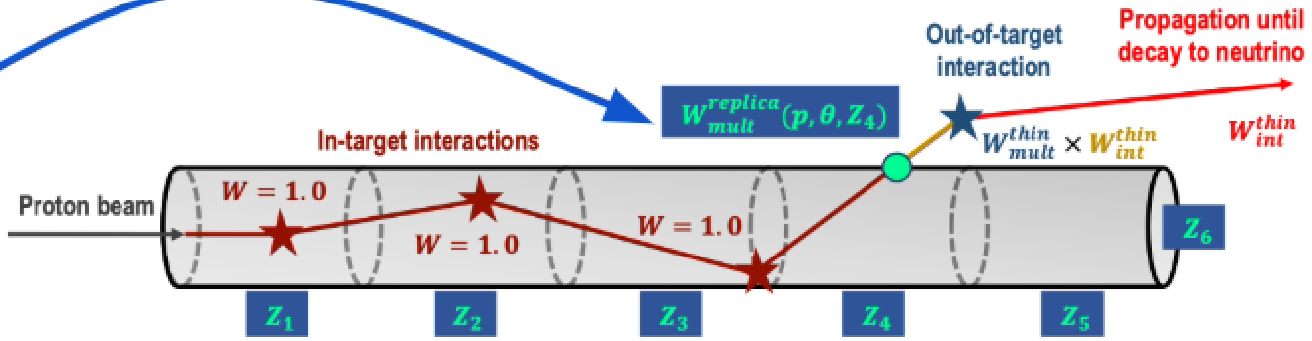
NA61/SHINE replica target based tuning

NA61/SHINE measurement:
p+T2K replica → $\pi^{\pm}$ / $K^{\pm}$ / p production

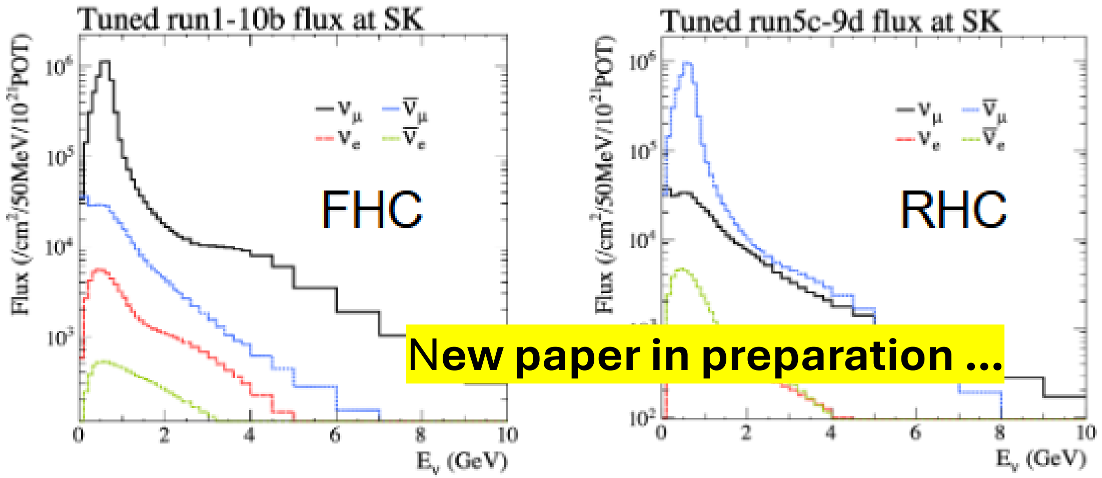


Eur. Phys. J. C **79**, no.2, 100 (2019)

Input for replica target based tuning



Tuned T2K flux

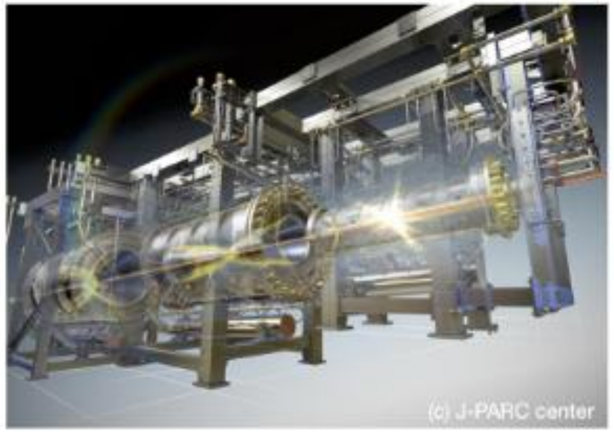


New paper in preparation ...

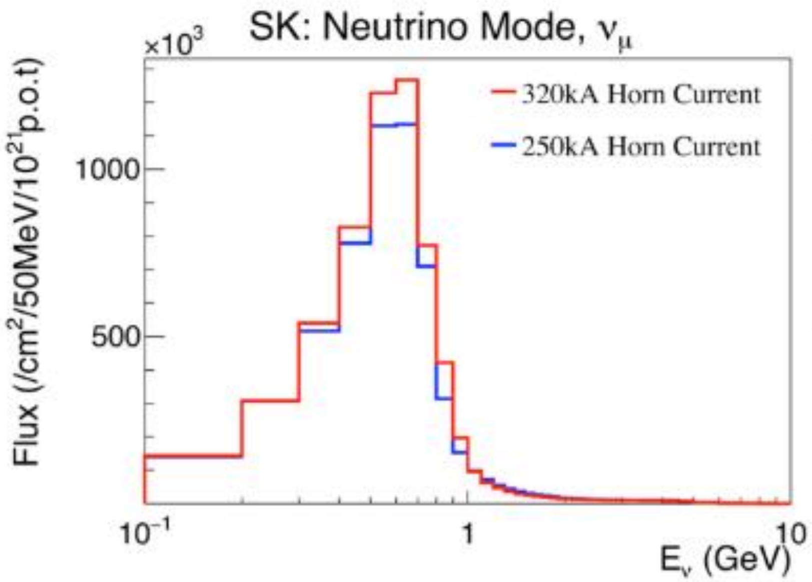
1

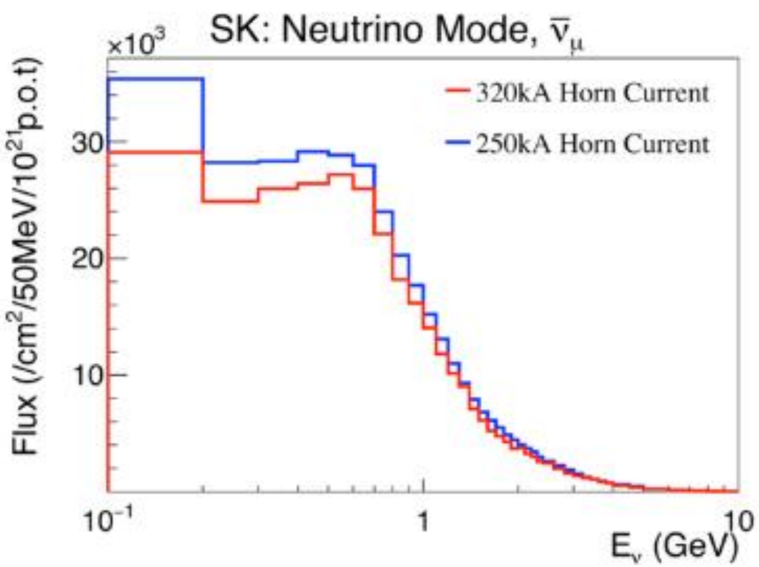
Slide from Y. Nagai

Recent Upgrade on Horn Current



Upgrade of the horn current (±250 kA → ±320 kA) improves the neutrino beam quality

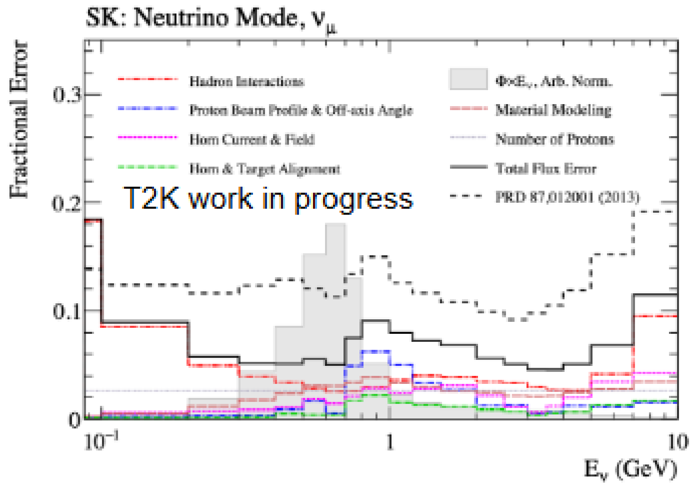




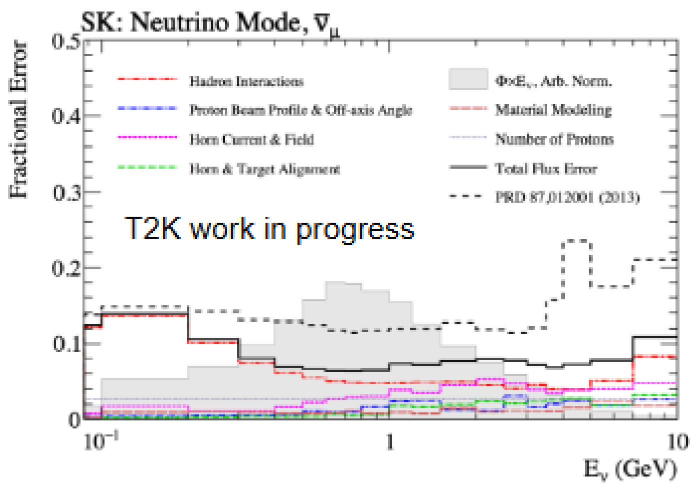
Increase in right-sign neutrinos (~10% for νμ at peak)
Decrease in wrong-sign neutrinos (~7% for νμ at peak)

Slide from Y. Nagai

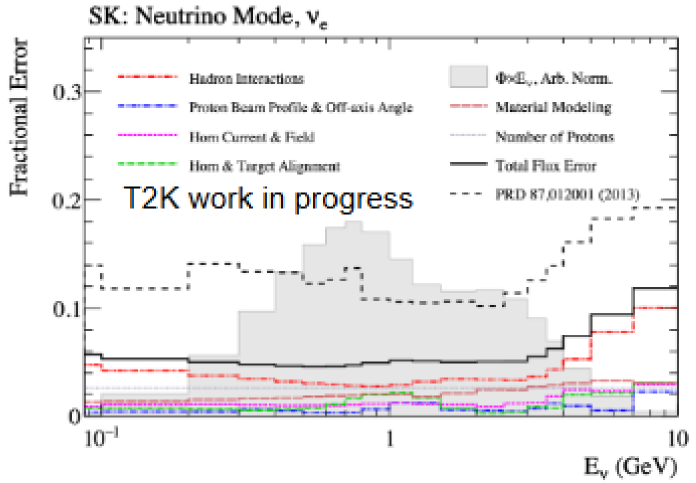
Current Understanding on the T2K Flux Uncertainty



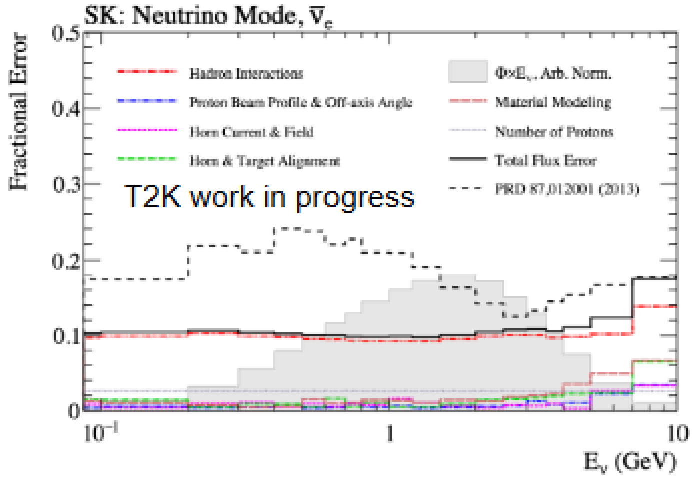
(a) Right-sign ν_μ



(b) Wrong-sign ν_μ



(c) Right-sign ν_e



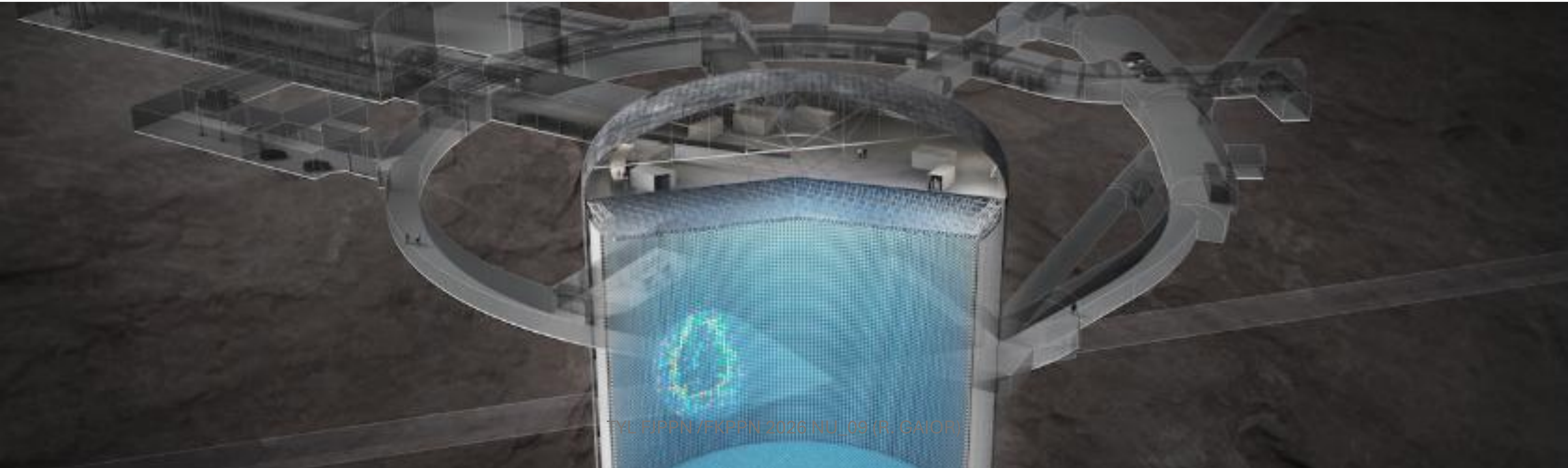
(d) Wrong-sign ν_e

Total flux error: key findings

- **~5% near the flux peak**
- At higher and lower energies, a significant contribution from **Hadron Interactions**
- Non-hadronic sources (Material modeling, Proton beam, Horn) become a primary source of error for several phase spaces

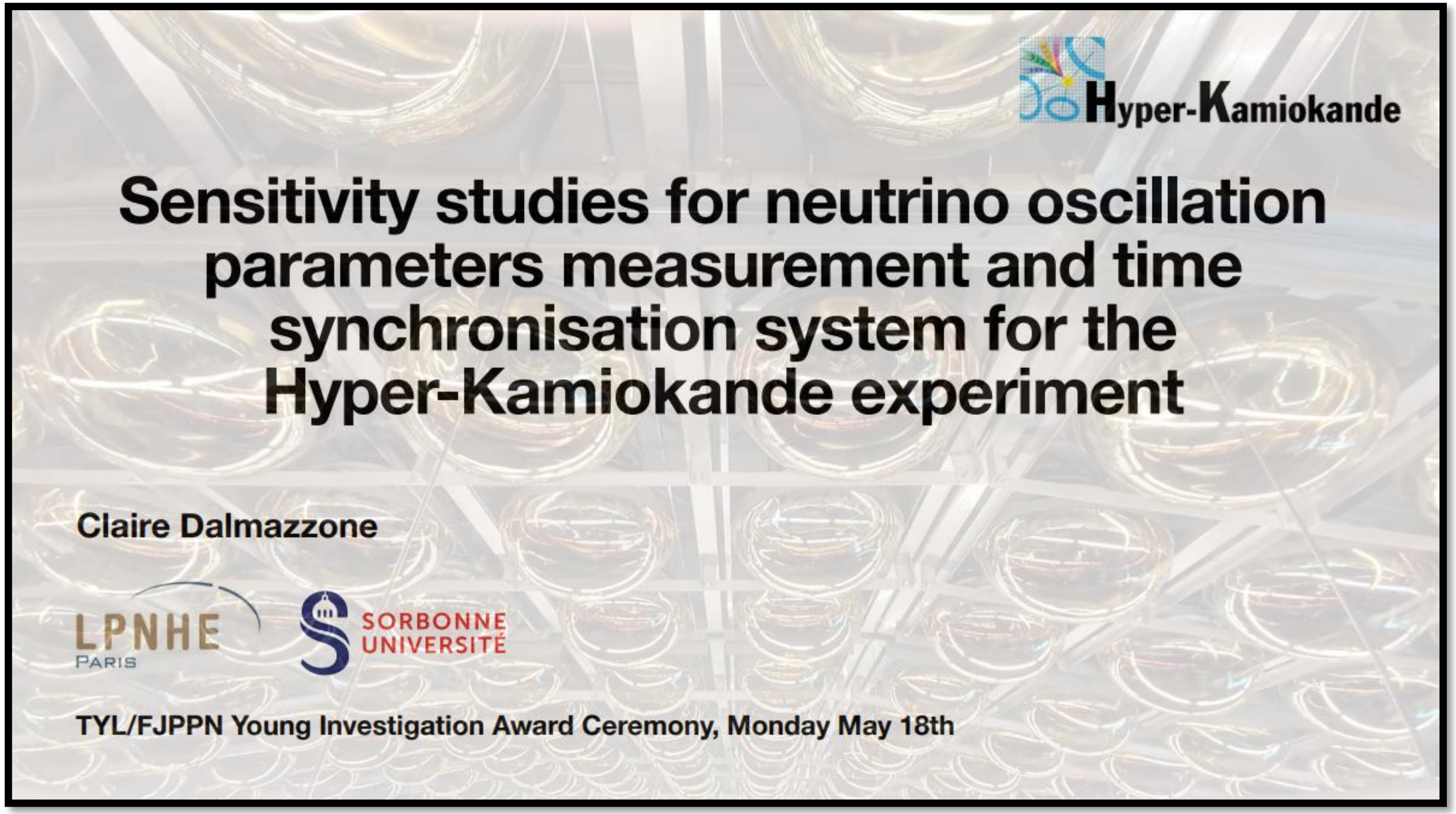
Slide from Y. Nagai

Hyper Kamiokande:
Sensitivity studies
Timing system development

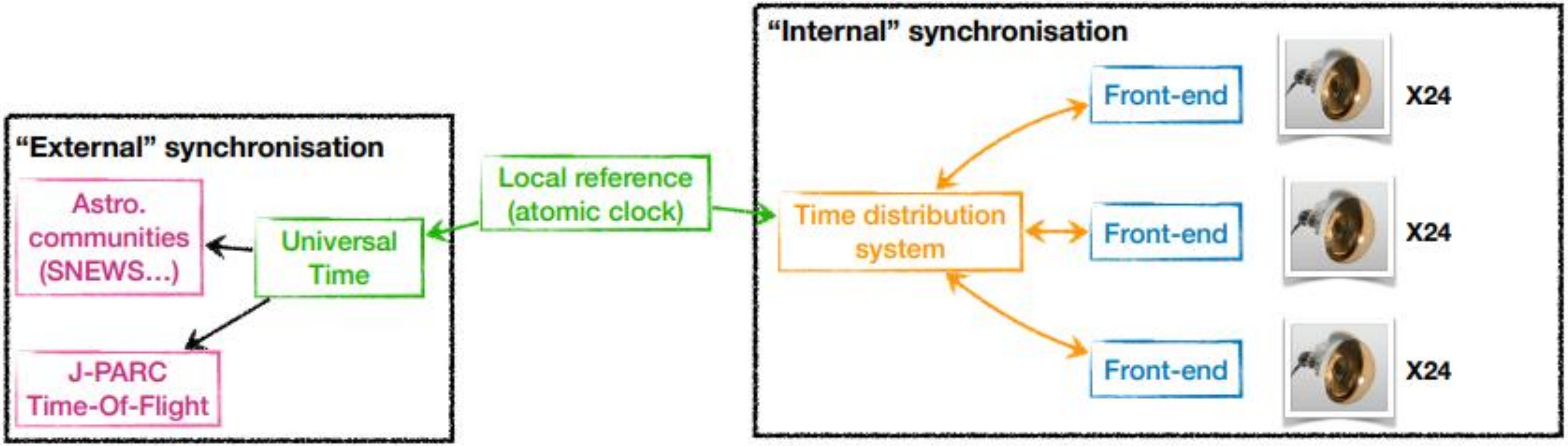


Sensitivity studies

See the award winner talk !
(Monday 18/05)

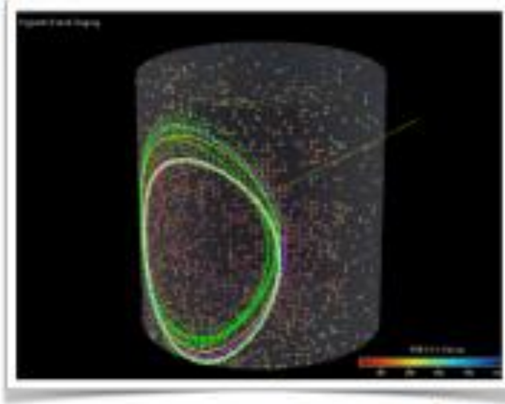


Timing system development for HK



Correlation with external experiments (J-PARC Time-Of-Flight, Supernovae...)
→ event time-tagging < 100 ns using GNSS receivers

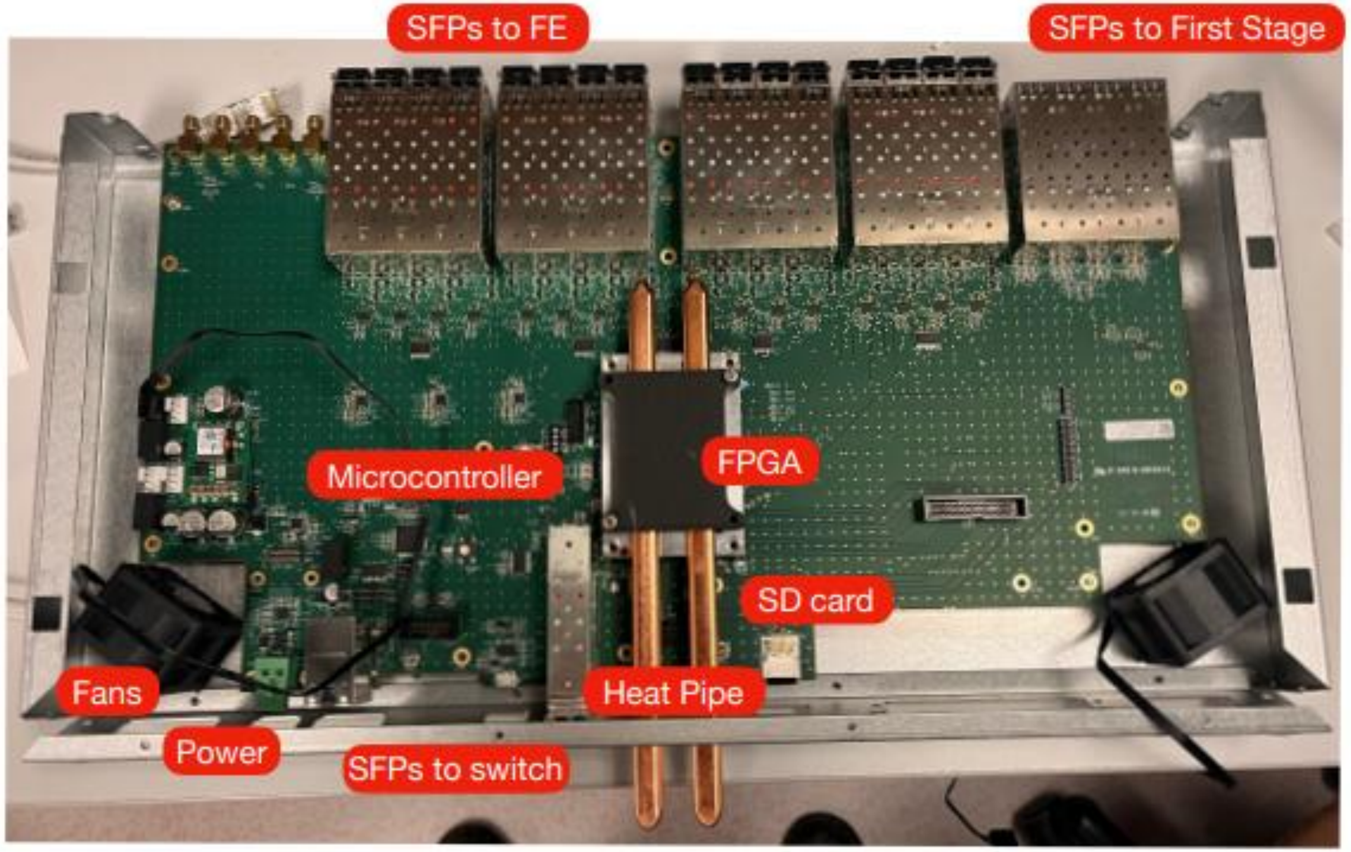
Rings reconstruction by coincidence
→ time difference between PMTs < 100 ps
→ constant skew after reset



Slide stolen from M. Guigue (EPS2025)

The Time Distribution Module

- The TDM board is designed to:
  - Receive master clock and distribute it with jitter at the endpoint < requirement
  - Guarantee a constant channel to channel phase difference over each reset and power up compensating the differences introduced by different cable lengths
  - Guarantee a bidirectional data bandwidth > 100 Mbps
  - Communicate to the DAQ system to exchange slow control data.
  - Redundant optical fiber link to each FE to be activated by a software command

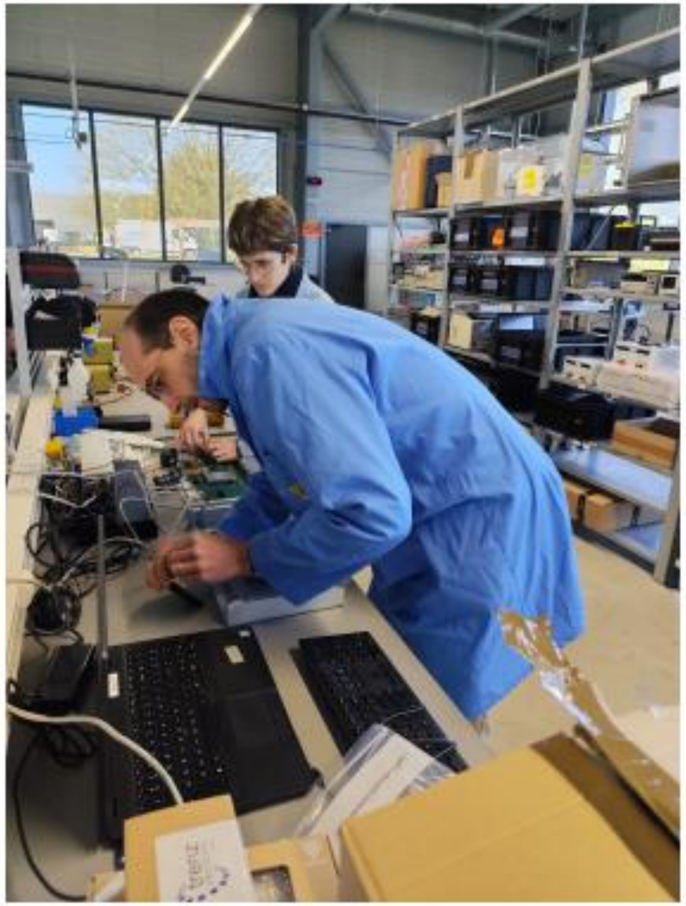


- Main element : a Xilinx XCZU9EG Zynq ultrascale+ SoC FPGA
  - FPGA comes pre-assembled on a electronics board hosting main power supply section, a double data rate (DDR) memory for the processor etc… no complex routing on the board
  - Link between the TDM and the system-on-module with 4 high-speed connectors with 160 pins each

Slide from M.A. Sabia

Integration: assembly procedure

- Assembly and testing procedure ready to be handled to external company (OUESTRONIC)
  - Goal: screening of faulty components and bad solderings
  - Procedure:
    - Physical installation: populated board fixed on a dedicated support, external components are mounted (mezzanine module, SFPs, SD card and cables)
    - Automatic tests: board switched on, ID info collected and network configured. Board parameters checked (voltages, current, temperature). Bit error rate measurement is done on all links.
    - Physical disassembly: the operator checks that data is collected and removes the SD card.



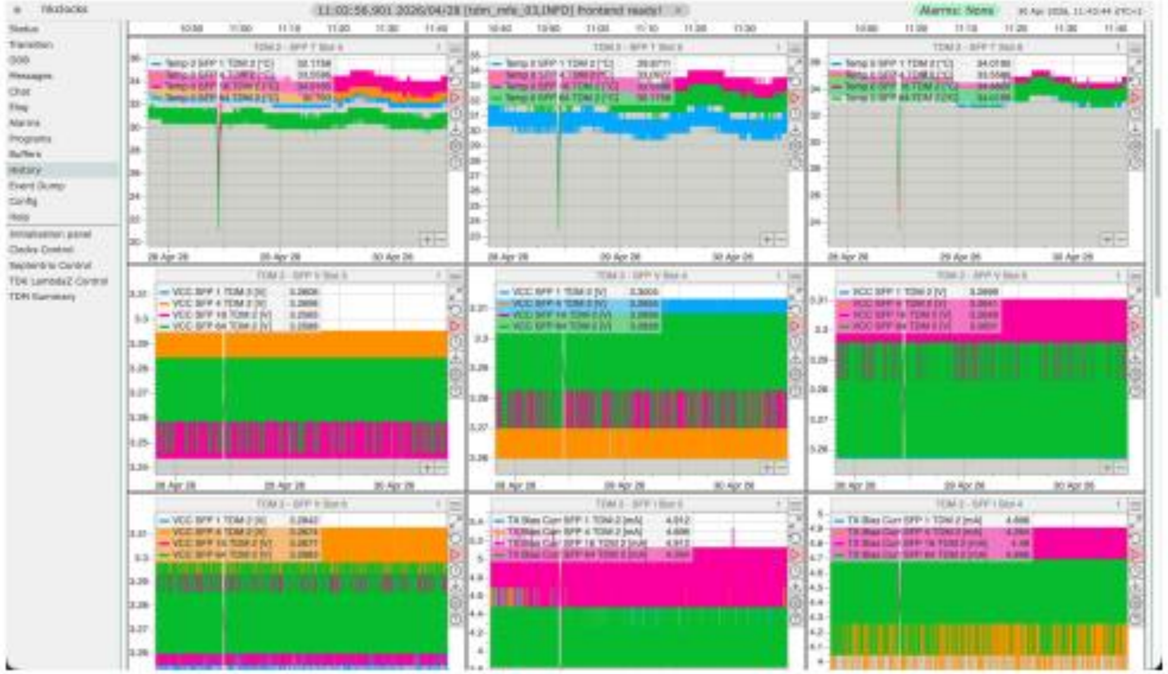
Demonstration @ OUESTRONIC

- At the end of the tests, the TDM is either ready to be used or declared faulty
- A report is posted on the github page of the tests.

Slide from M.A. Sabia

Integration

- Fully equipped rack to mimic the configuration at Hyper-K
- 4 latest version TDMs up and running
- One TDK Lambda power supply
- One switch
- External fans for additional ventilation (exploits the heat pipe)
- Slow control via MIDAS to monitor temperature, voltages etc.



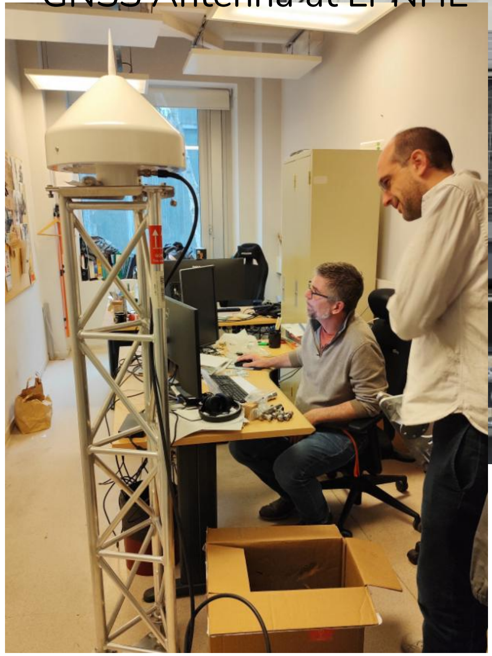
Slide from M.A. Sabia

Installation at JPARC

- Needs synchronization between the beam and far detector
  - Similar timing generation and distribution system needed at JPARC
  - Dedicated link between JPARC timing and TDM
- Antenna support designed at LPNHE
- Just shipped and Installed at JPARC
- Planned test (06/2026): integration of TDM board with the JPARC beam timing system

GNSS Antenna installed at JPARC Neutrino building

GNSS Antenna at LPNHE



Conclusion

- NU_09 project focused on the oscillation studies with T2(H)K:
  - Beam characterization (JPARC) and calibration (NA61/SHINE)
  - Development of timing system for HK
  - Sensitivity studies for HK

- Exciting time for the project:
  - NA61/SHINE:
    - Finalize and publish the K0s analysis
    - Measure the P and K yield → reduce flux uncertainties
  - T2K Beam:
    - Publish the use of target replica for the flux prediction and systematics reduction
  - Timing system:
    - Production in 2026
    - Integration and installation site in 2027