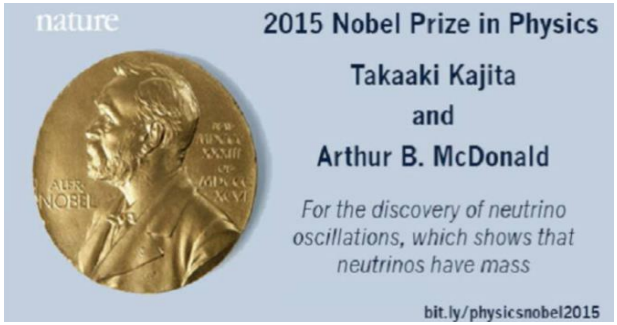
PhD projects (2) on T2K and nuSTORM

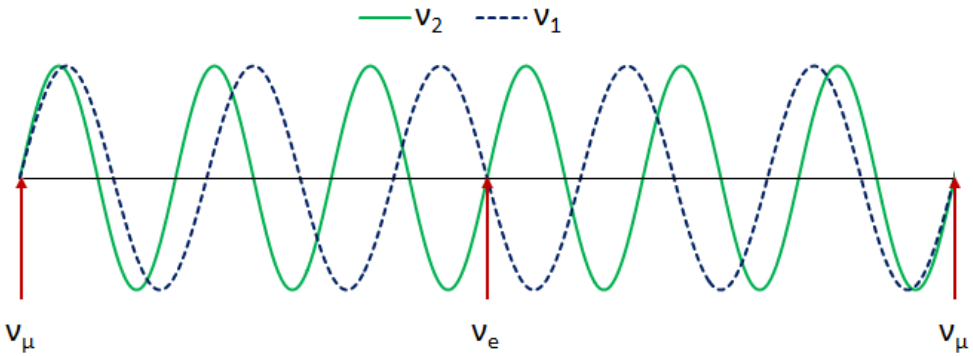
T2K: *Anna Holin* (STFC RAL), *Helen O'Keeffe* (Lancaster)

nuSTORM: *Xianguo Lu* (Warwick), *Stefania Ricciardi* (STFC RAL)

RAL PhD Open Day, 23 February 2023

Neutrinos: physics Beyond the Standard Model

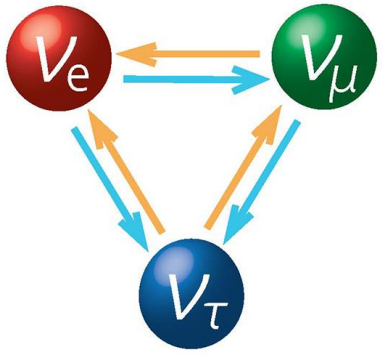




The discovery of neutrino oscillations has breached the Standard Model:

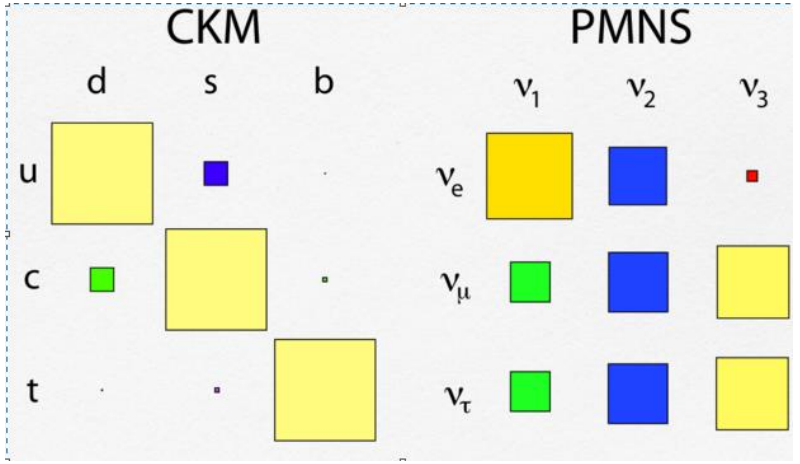
Neutrinos are NOT massless!

Lepton flavour is NOT conserved!



Neutrinos: open questions

- Mass: Why are neutrinos masses so small? Are neutrinos Dirac or Majorana particles? What's the mass ordering?
- Mixing:
  - Why is PMNS matrix so different from CKM?
  - Is the PMNS mixing matrix unitary?
  - Is CP violated in the neutrino sector?
- Exotic BSM phenomena
  - Are there sterile neutrinos?
  - Non-Standard Interactions? CPT violation?



Neutrino experiments have the potential to revolutionise our understanding of fundamental physics

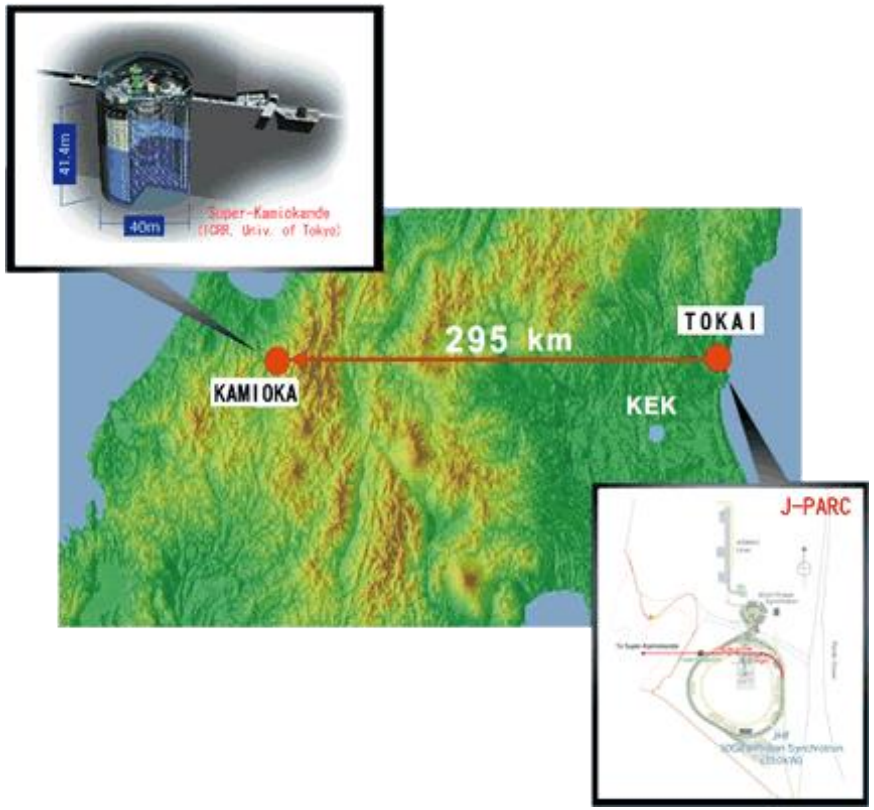


Image from T2K experiment https://t2k-experiment.org/

Leading the way to new discoveries in neutrino physics with T2K and Hyper-Kamiokande

Supervisors: Dr. Anna Holin (RAL, PPD) and Professor Helen O'Keeffe (Lancaster)

The Tokai to Kamioka (T2K) experiment

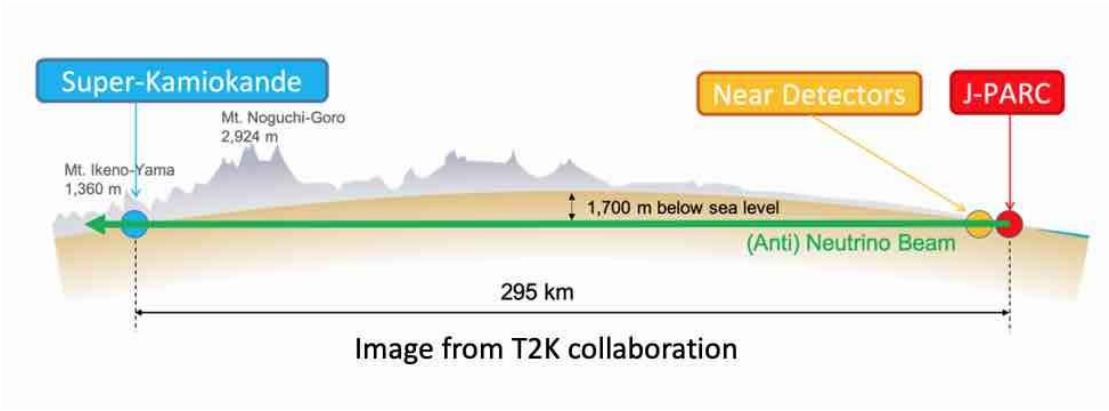
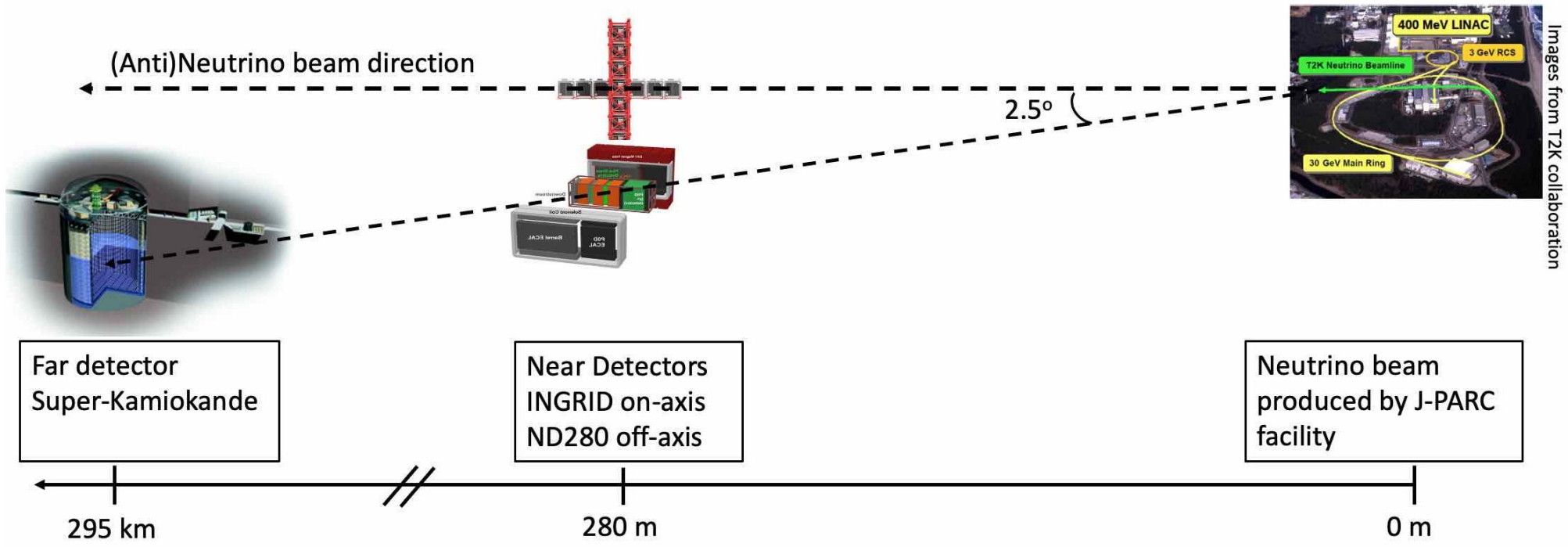


Image from T2K collaboration



T2K (anti)neutrino beam

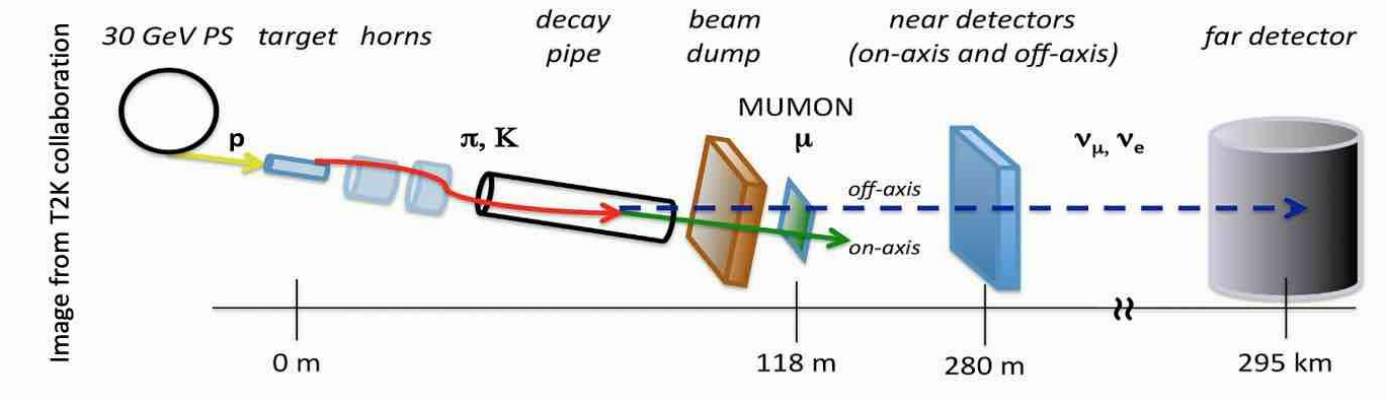
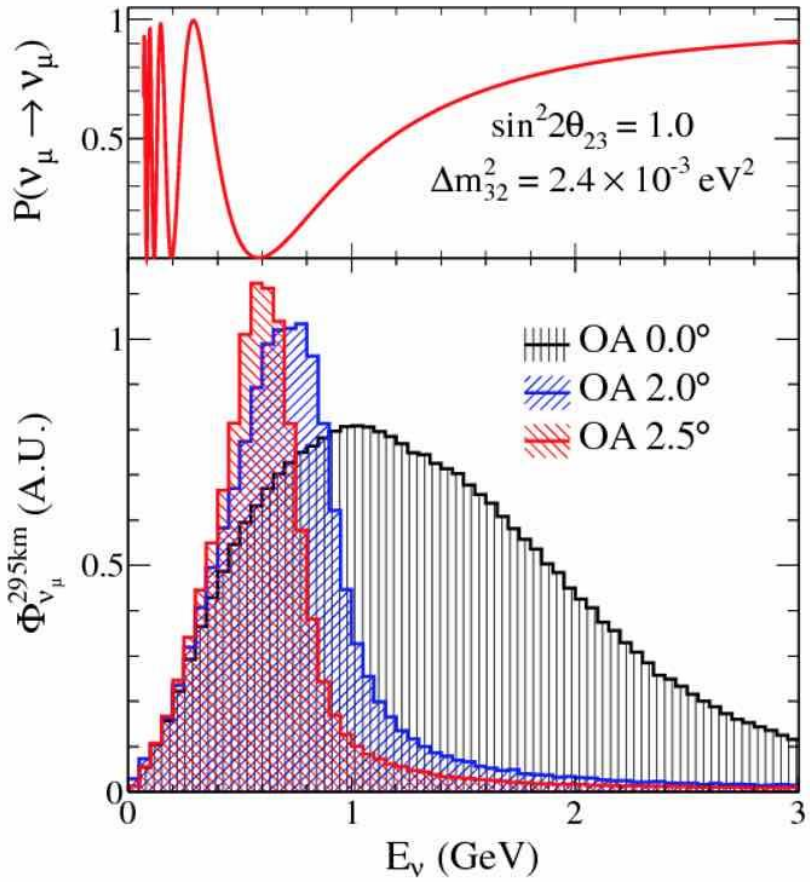


Figure from 10.1103/PhysRevD.87.012001



High-purity ν_μ beam

- Reverse horn current to produce anti-ν_μ beam
- Place detectors 2.5° off the beam axis to increase the proportion of neutrinos within the beam that have a higher oscillation probability

T2K detectors

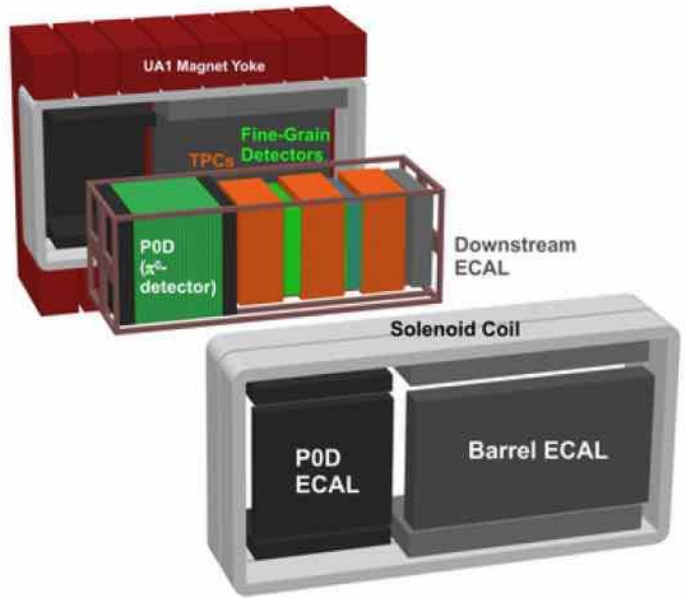
Near detectors

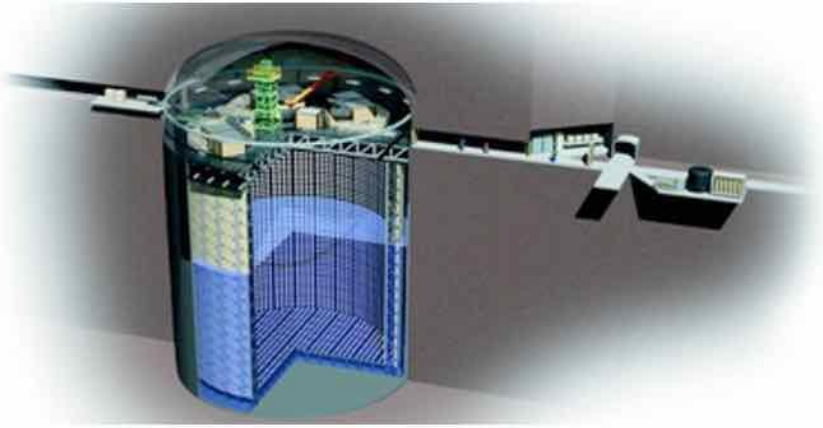
- Determine initial composition of the beam before oscillation (at 280 m)
- Measure intrinsic electron (anti)neutrino component
- Measurements of interaction cross sections
- Upgraded near detector is being installed now!

Far detector

- Measure composition of the beam after 295 km
- $\nu_\mu \rightarrow \nu_e$ appearance and $\nu_\mu \rightarrow \nu_X$ disappearance
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance and $\bar{\nu}_\mu \rightarrow \bar{\nu}_X$ disappearance

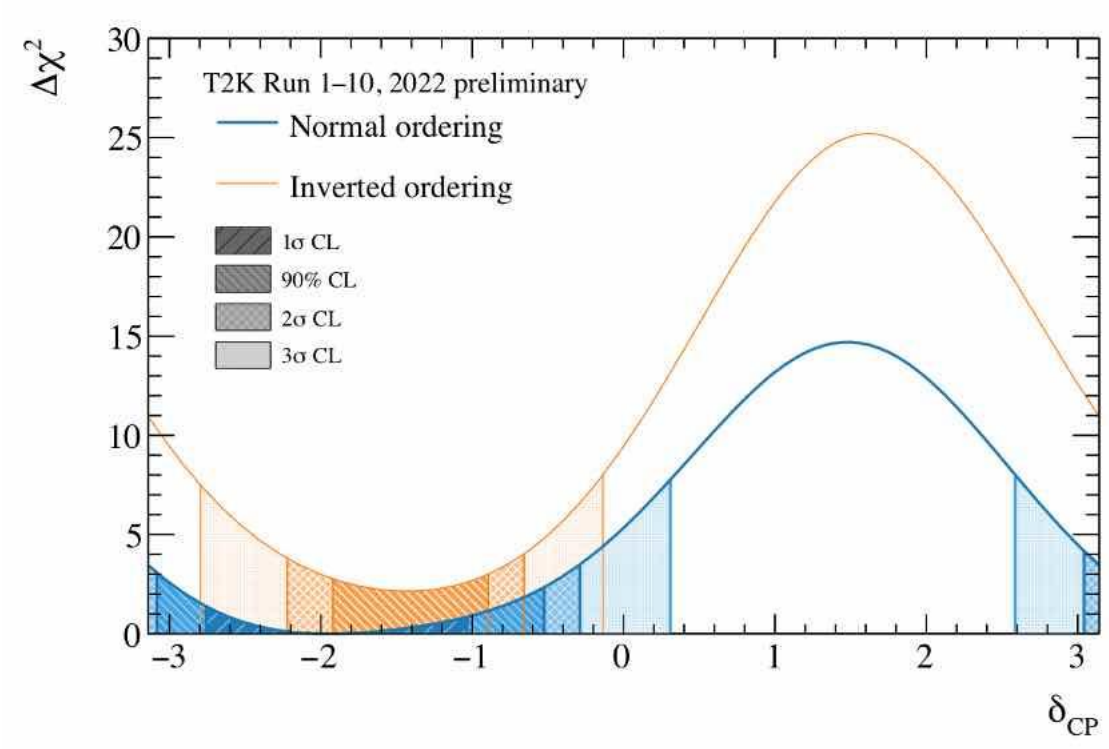
Compare measured compositions at near and far detectors to determine that neutrino oscillation has taken place.

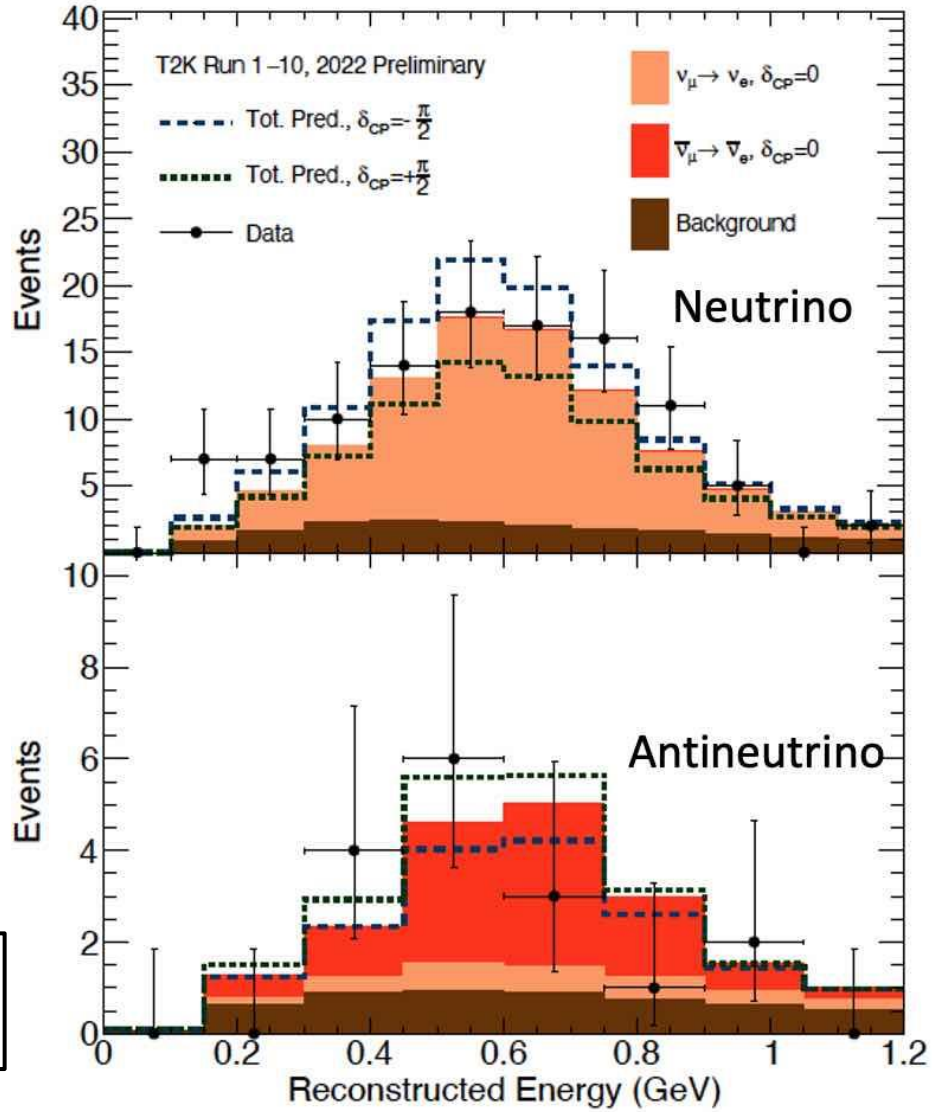




Images from T2K collaboration

Neutrino oscillations at T2K





- Large region of δ_{CP} excluded at 3σ
- CP-conserving values $\delta_{CP} = 0$, $\delta_{CP} = \pi$ are excluded at 90% CL

Beyond T2K: Hyper-Kamiokande

Next-generation water Cherenkov detector

- Located in the Kamioka mine, Gifu prefecture at a baseline of 295 km from J-PARC
- Cylindrical detector filled with ultra-pure water
  - 68 m diameter, 71 m height
  - 258 kton of water -> 8 x Super-K fiducial volume
- Inner detector:
  - Instrumented with 20,000 PMTs (20” diameter) with improved photon detection
  - Multi-PMT assemblies consisting of 19 individual 3”PMTs
- Outer detector:
  - 3” diameter PMTs with wavelength shifting plates

Construction began in 2020!

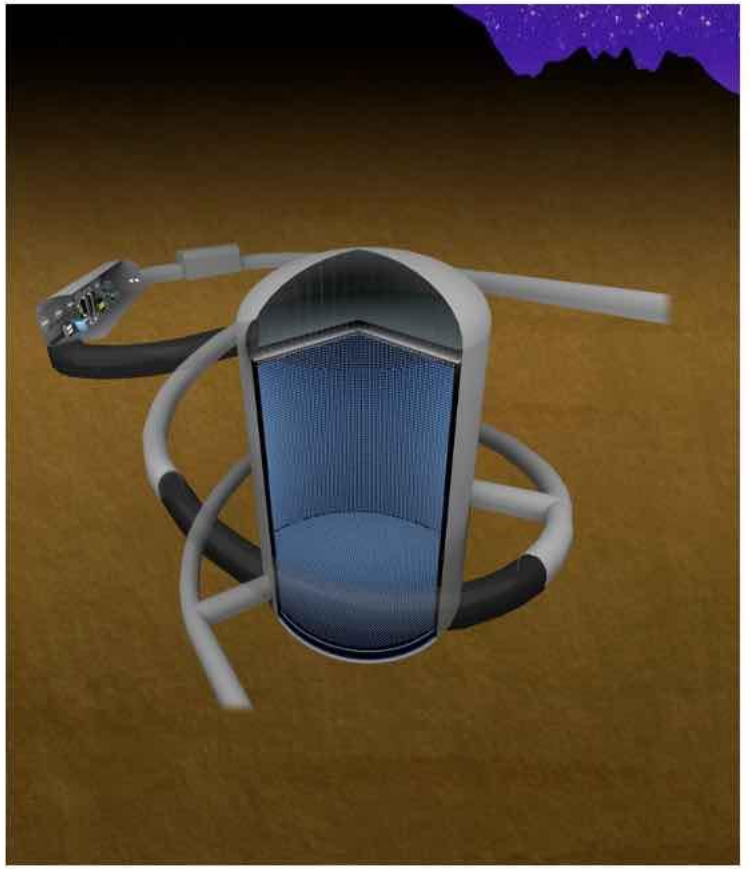


Figure from Hyper-Kamiokande collaboration

T2K/Hyper-Kamiokande thesis

Supervisors (both here in person today!)

Anna Holin, RAL PPD

Helen O'Keeffe, Lancaster University

Thesis topic

- Mainly T2K, but with some Hyper-K
  - Measuring CP-violation with T2K
  - Use ND constraints to reduce systematic uncertainties
  - Measure neutrino cross sections
  - Opportunity to prepare for T2K-II/Hyper-K
- Opportunity to assist with on-site support for T2K near detector
  - Simulations/lab measurements/potentially on-site opportunities for Hyper-Kamiokande

Student will be based 50% at RAL, 50% at Lancaster.

Opportunity for long-term attachment (LTA) in Japan

UKRI Science and Technology Facilities Council

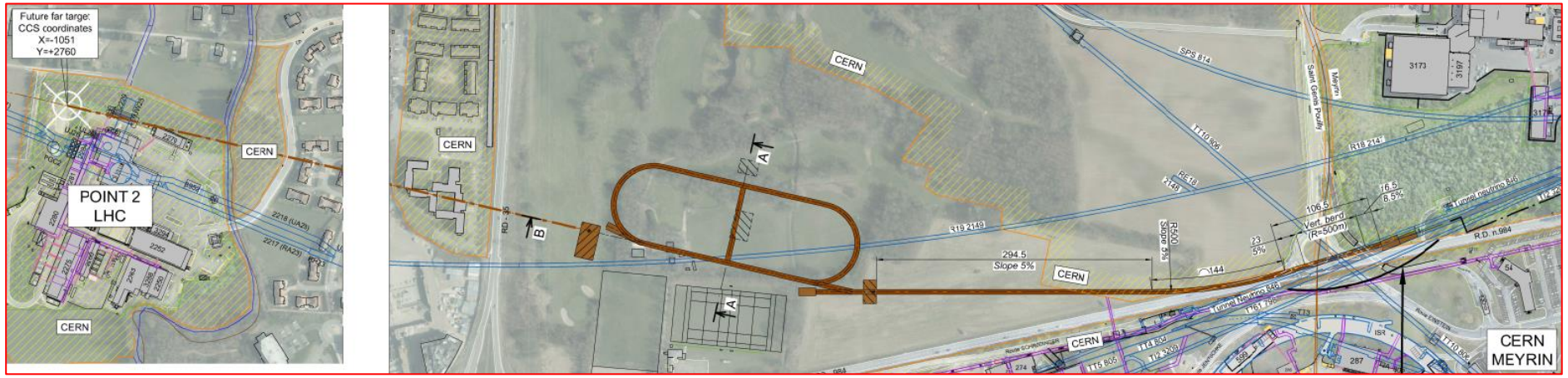
Particle Physics

Lancaster University

T2K

Hyper-Kamiokande

C. C. Ahdida et al., “nuSTORM at CERN: Feasibility Study,” CERN-PBC-REPORT-2019-003



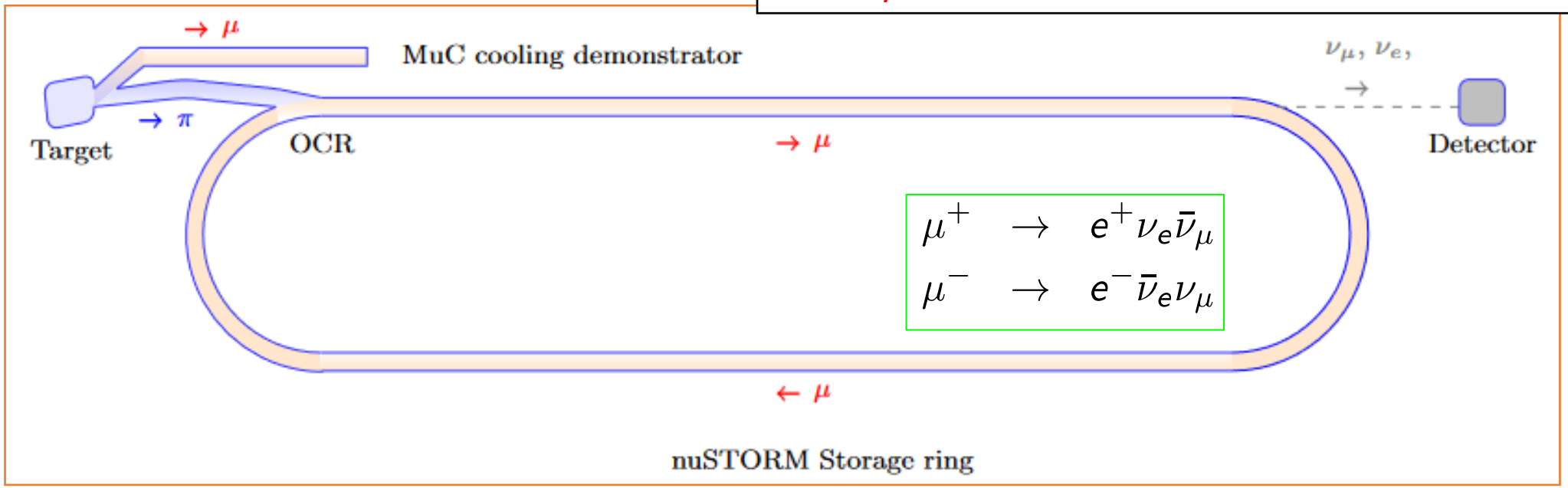
Ultimate neutrino flux optimisation and design of next-generation neutrino experiments in νSTORM

Supervisors: Dr. Xianguo Lu (Warwick) and Dr. Stefania Ricciardi (RAL, PPD)

What is nuSTORM?

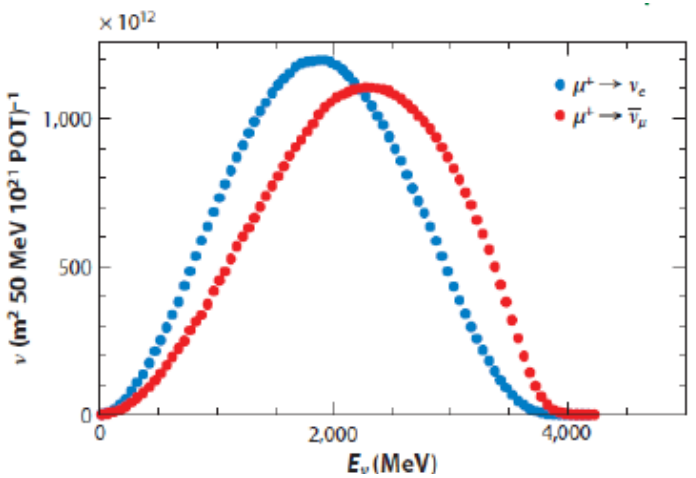
Neutrinos from STORed Muons

a facility for neutrino oscillation and BSM searches



$\pi^+ \rightarrow \mu^+ \ \nu_\mu$ Pion-flash

$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$ Stored muons



Adey et al., Annu. Rev. Nucl. Part. Sci. 2015.65

Precise neutrino flux:

- Well-known energy spectrum
- Unique flavour composition

$$(\nu_e : \overline{\nu_\mu}) = (1 : 1)$$

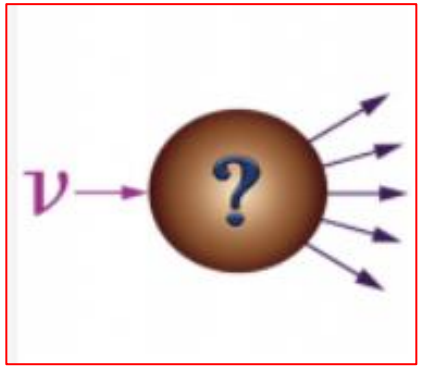
- Rate uncertainty < 1%

Why nuSTORM?

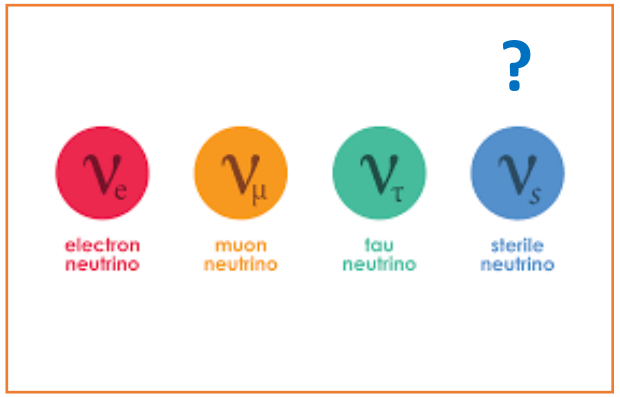
Multi-purpose: particle physics and accelerator development

- Superb (%-level precision) measurements of

  neutrino-nucleus cross-sections in the few-GeV region
  - greatly benefit future neutrino oscillation program
  - progress in hadron and nuclear physics



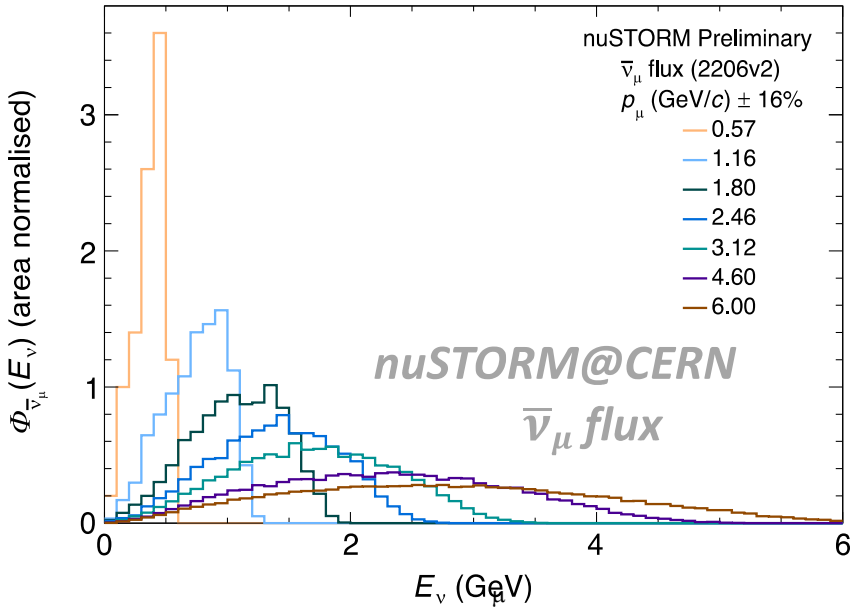
- Sensitive searches for BSM physics at short-baseline
  - potential to discover and study sterile neutrinos
    (high-sensitivity in region allowed by LSND/MiniBoone)
  - constrain Non-Standard Interactions and other exotic processes

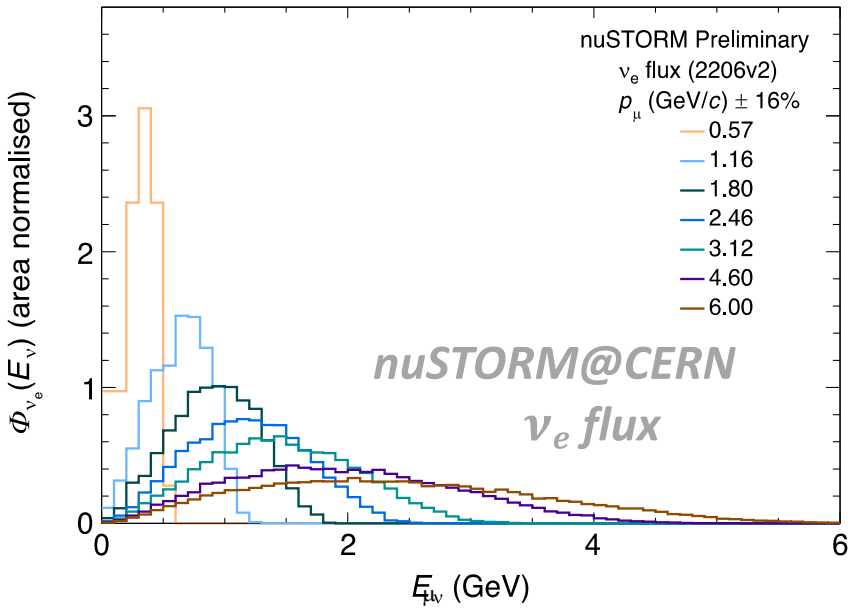


- Muon Collider demonstrator
  - Muon storage ring of large acceptance
  - Instrumentation for muon-beam monitoring

nuSTORM@CERN: neutrino beam spectra

nuSTORM, arXiv:2203.07545





- Oscillation-relevant energy regime
  - Hyper-K: 0.6 GeV
  - DUNE : 2.4 GeV
- Set by stored-muon momentum
- Accelerator "tune" gives fine control
  - E.g. optimise flux shape (or spread) by adjusting the ring acceptance

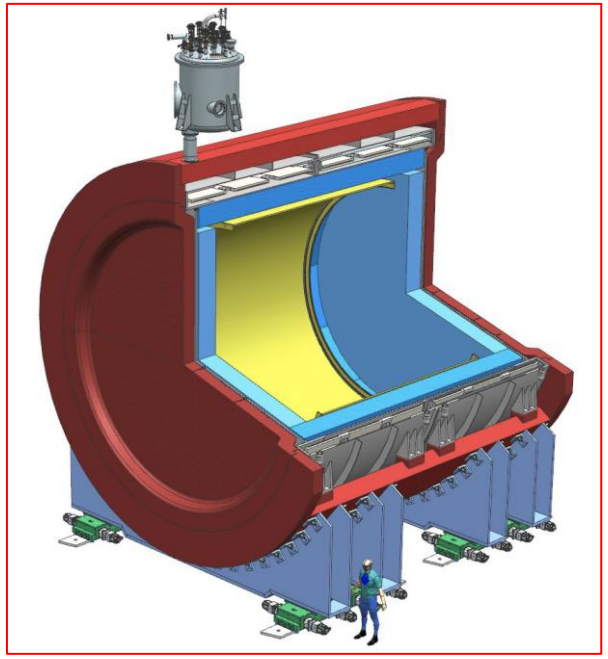
- Unique opportunity:
  - E_ν-scan measurements
  - Monoenergetic flux (ν_e!!) emulated by flux combination

nuSTORM detector

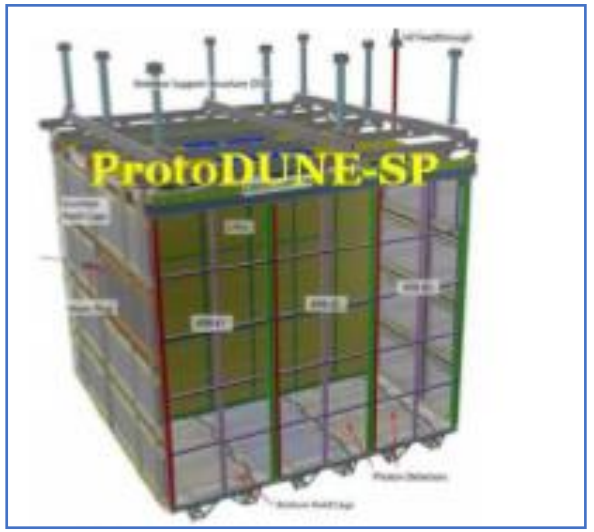
- Initial study uses DUNE ND-GAr:

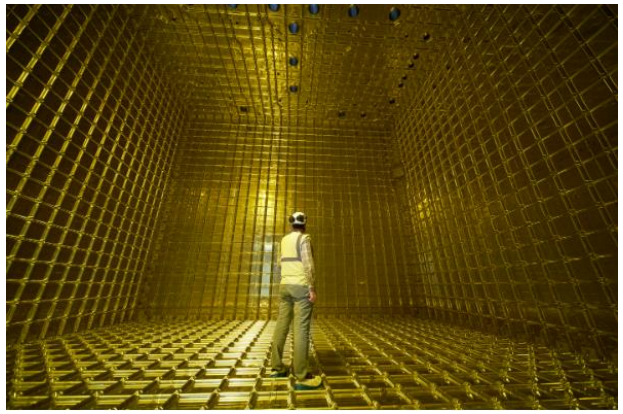
  High-Pressure Gas TPC

DUNE, instruments **5**, 31 (2021)



- An alternative option: LAr TPC





nuSTORM: student's project outline

Main objectives:

Determine nuSTORM sensitivity to ν_e and ν_μ cross-sections measurements;

make quantitive comparisons to expectations from Hyper-K and DUNE

1. Develop nuSTORM state-of-the-art simulation to improve design of beamline and detector
2. Explore novel ideas to produce mono-energetic neutrino fluxes
3. Perform studies of neutrino cross-section measurements
4. Consolidate the beamline and detector designs

Bonus track: sensitivity studies of Heavy Neutral Leptons searches

Student will be based at Warwick and at RAL (50% time at each site)

Opportunity to spend a period at CERN on LTA (Long Term Attachment)

Conclusion

Two exciting PhD projects!

T2K/Hyper-K

- Upgraded T2K near detector is being installed now!
- Mainly software/analysis project but possible to become involved with on-site operations and/or lab-based measurements
- Opportunity to contribute to the development of the next-generation Hyper-Kamiokande experiment

nuSTORM

- New facility concept: unique precise ν_e/ν_μ source for neutrino physics and major step towards muon collider
- Software/analysis project involving accelerator/detector simulation and physics sensitivity studies
- Opportunity to influence beam and detector design choices at an early stage

Would you like to join? Please sign up for a chat in person today or via Zoom tomorrow