Physics | Lancaster University

Neutrino Oscillations

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Overview

- Status of Neutrino Oscillation Physics.
- Fundamental Physics Questions.
  - Addressing these questions…
- 2013 European Strategy Update.
  - DUNE, Hyper-K, CERN Neutrino Platform.
- Future European Strategies.
  - Focus on accelerator neutrinos.

Neutrino Oscillations

- The current generation of oscillation experiments has precisely measured most parameters of the standard oscillation model.

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}\,e^{-\iota\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}\,e^{+\iota\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

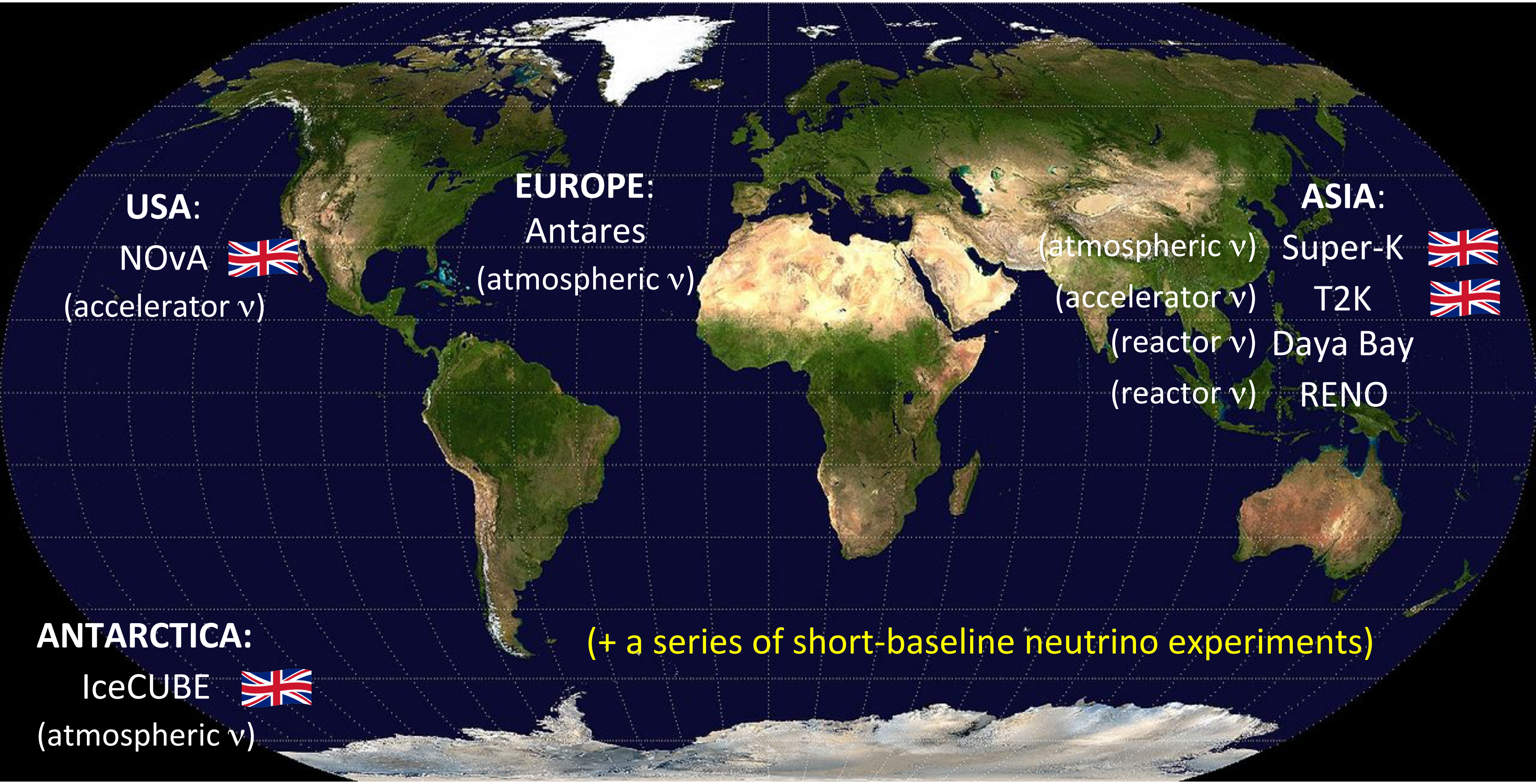
FLAVOUR STATES **PMNS MIXING MATRIX** **MASS STATES**

Parameter	Global Fit	Precision
θ_{12}	33.6 ± 0.8	2%
θ_{13}	8.5 ± 0.2	2%
θ_{23}	42 ± 2	5%
Δm^2_{21} / 10^{-5} eV^2	7.5 ± 0.2	3%
$\lvert\Delta m^2_{32}\rvert$ / 10^{-3} eV^2	2.52 ± 0.04	2%
δ_{CP}	(Not yet precisely measured)	

Numbers from Esteban et al, JHEP 01 (2017) 087

Ocillation Experiments

◆ Current generation of long-baseline neutrino oscillation experiments:



= UK involvement (ranging from 1 to 10 institutions)

Oscillation Measurements

Accelerator neutrinos (e.g. T2K)

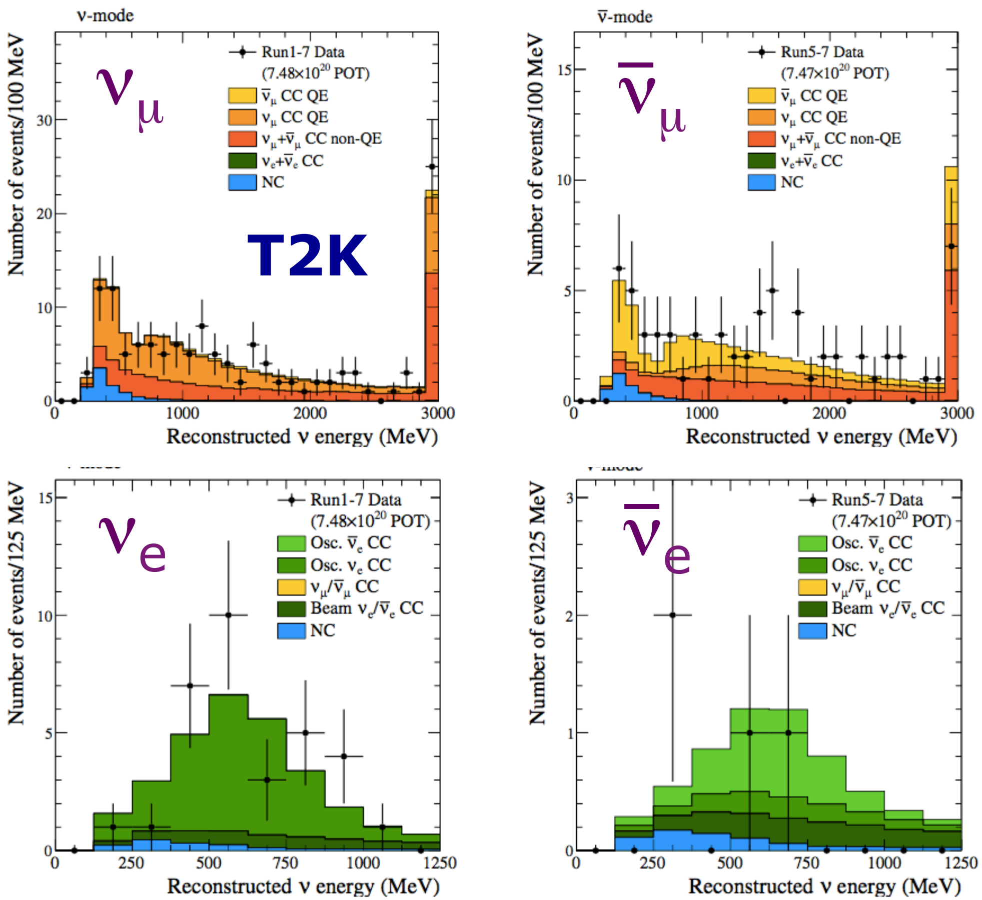
Δm^2_{32} and θ_{23} from ν_μ disappearance

θ_{13} and δ_{CP} from $\nu_\mu \rightarrow \nu_e$ appearance.

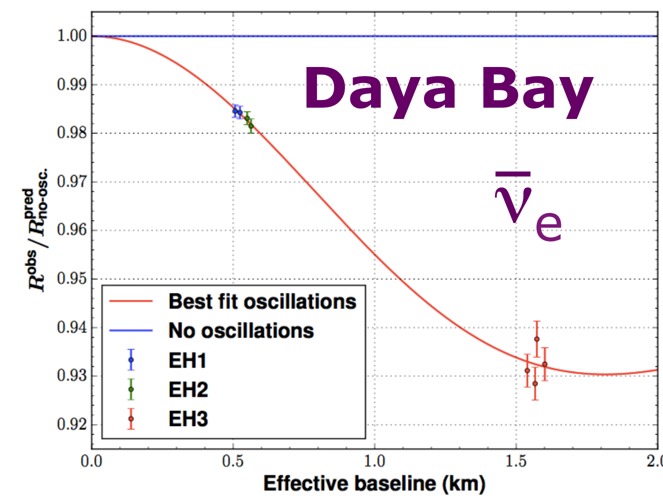
Reactor neutrinos (e.g. Daya Bay)

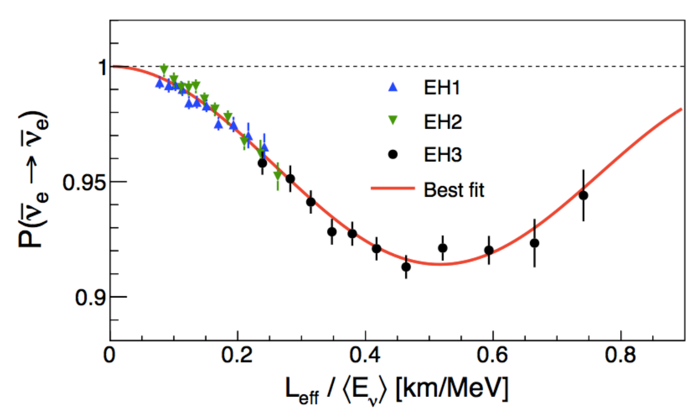
Δm^2_{32} and θ_{13} from ν_e disappearance

T2K - PRD 96, 092006 (2017)



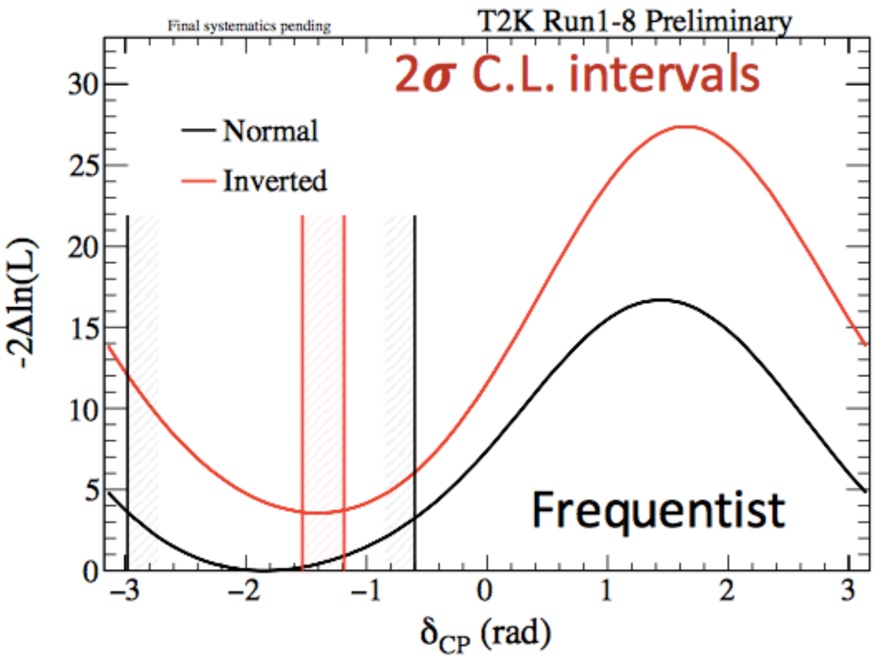
Daya Bay - PRD 95, 072006 (2017)



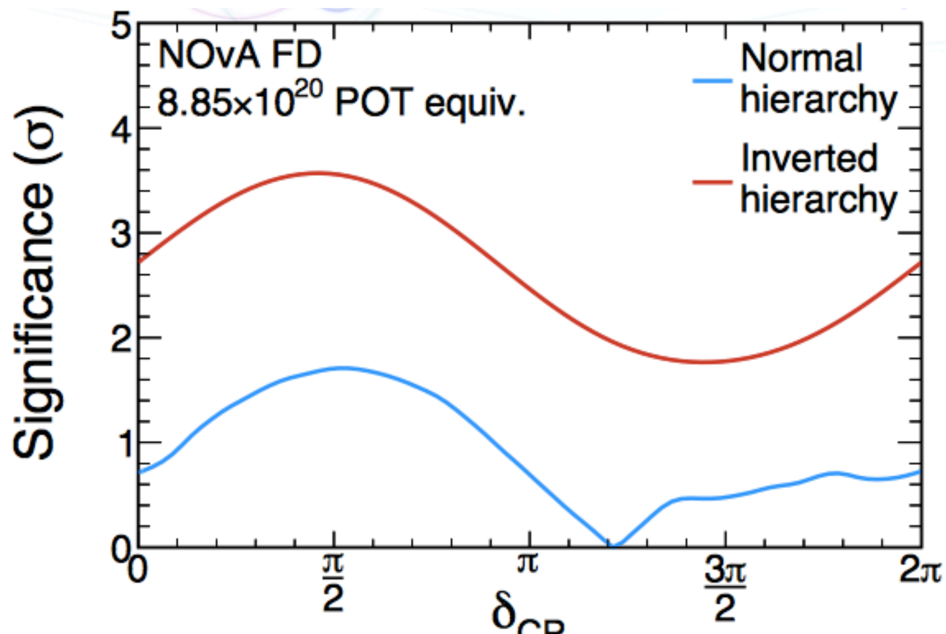


Oscillation Measurements

- Results from operating long-baseline accelerator neutrino experiments (T2K and NOvA) are in good agreement.
  - Consistent measurements of Δm^2_{32} (~2.5×10^{-3} eV^2) and θ_{23} (~45°).
- Both experiments have also observed the first hints of a non-zero δ_{CP}, reporting similar best-fit values around δ_{CP}~$3\pi/2$.



S Cao (Moriond'18)

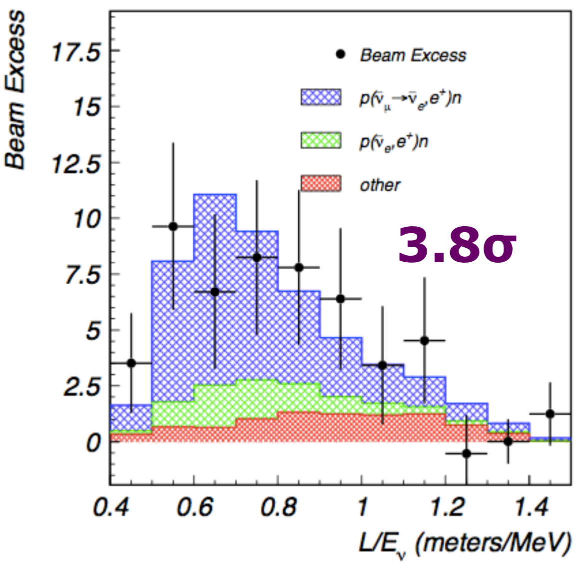


C Backhouse (Moriond'18)

Short-baseline Tensions

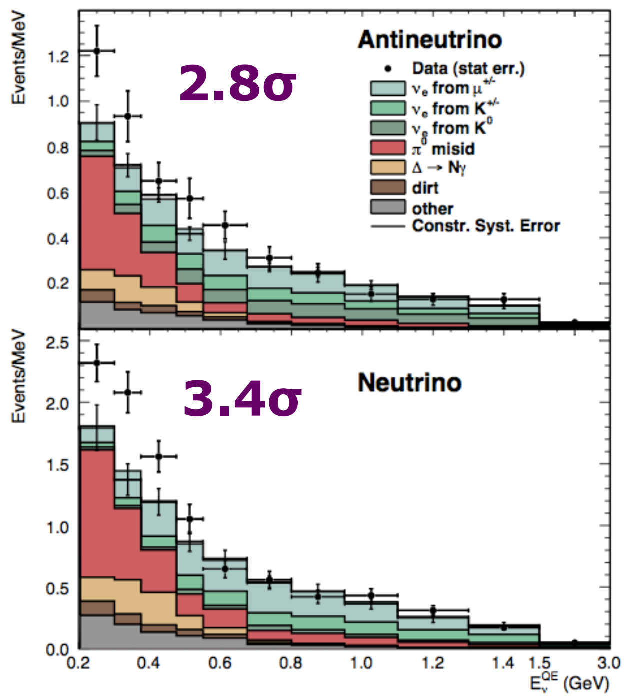
- While the bulk of the world's data are consistent with standard oscillations, a number of results from short-baseline experiments exhibit tension.
  - ➢ LSND; MiniBooNE; Gallium calibration sources; Reactor anomalies.
- These tensions are often used to motivate a ~1eV sterile neutrino.

LSND



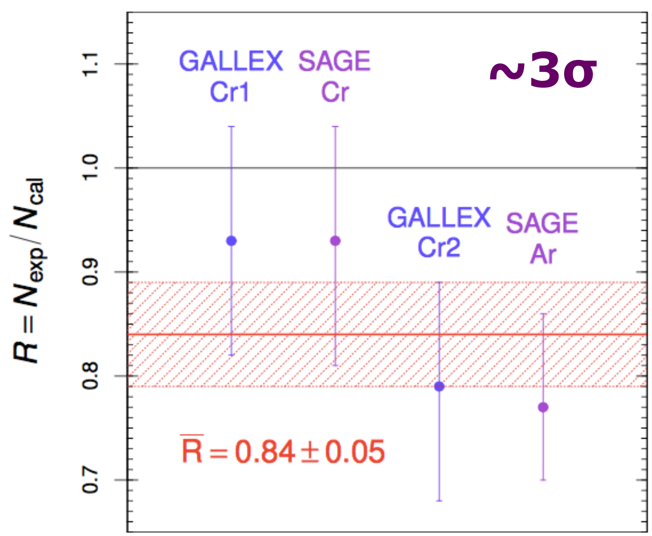
PRD 64, 112007 (2001)

MiniBooNE



PRL 110, 161801 (2013)

SAGE/GALLEX



C. Giunti (Neutrino'16)

Fundamental Physics Questions

- A number fundamental physics questions remain to be (definitively) addressed by future neutrino oscillation experiments:

(1) Is there CP violation in the lepton sector?

i.e. Does $P(\nu_\mu \rightarrow \nu_e) \neq P(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e)$?

Equivalently, does $\delta_{CP} \neq 0,\pi$?

(2) Do neutrinos have a 'normal' or an 'inverted' mass ordering?

i.e. Does $m_3>m_2$ or $m_3<m_2$?

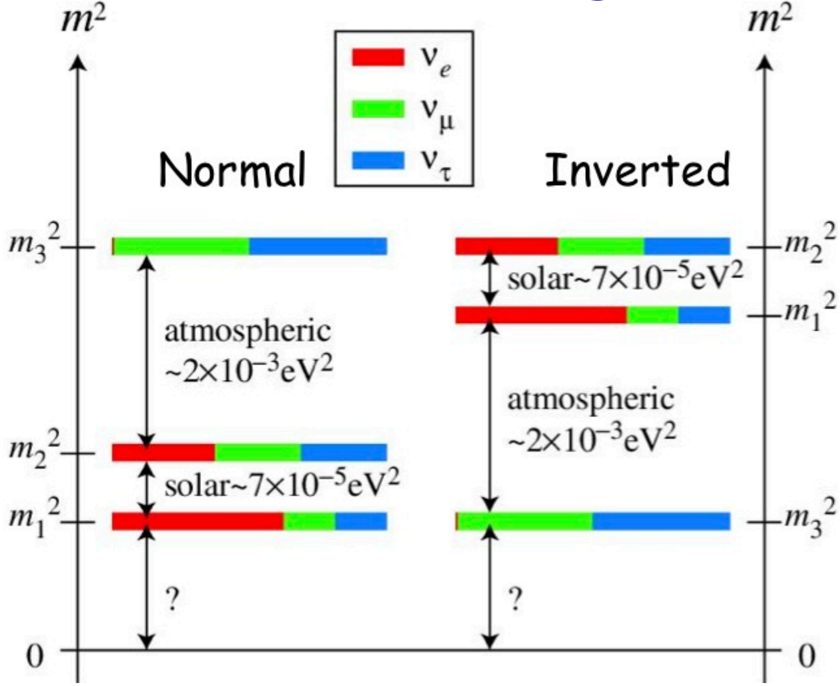
(3) What is the octant of the angle θ_{23}?

i.e. Does $\theta_{23}<45°$, $\theta_{23}>45°$ or $\theta_{23}=45°$?

(4) Is there physics beyond the standard three-flavour model of oscillations?

e.g. sterile neutrinos, non-standard interactions, etc…

Mass and mixing



Addressing These Questions

- To address these questions, need a new **international programme of high-precision long-baseline neutrino experiments**.
  - High-intensity accelerator neutrino beams.
  - Multiple detectors.
- To study oscillations with the required level of precision, also need a strong accompanying **theoretical** and **experimental** effort.
  - A detailed understanding of neutrino flux and interaction physics will be needed to control systematic uncertainties.
    - Will need improved theory and experimental data in the areas of hadroproduction, neutrino cross-sections, etc…
  - Next generation of experiments will require improved hardware, computing, online/offline software, etc…
  - Should also characterise detectors using test beams.
- Short-baseline signals must be addressed with dedicated experiments.

European Strategy Update (2013)

- The previous European Strategy Update (coupled with the parallel P5 process in the USA) established a clear pathway:

High-priority large-scale scientific activities:

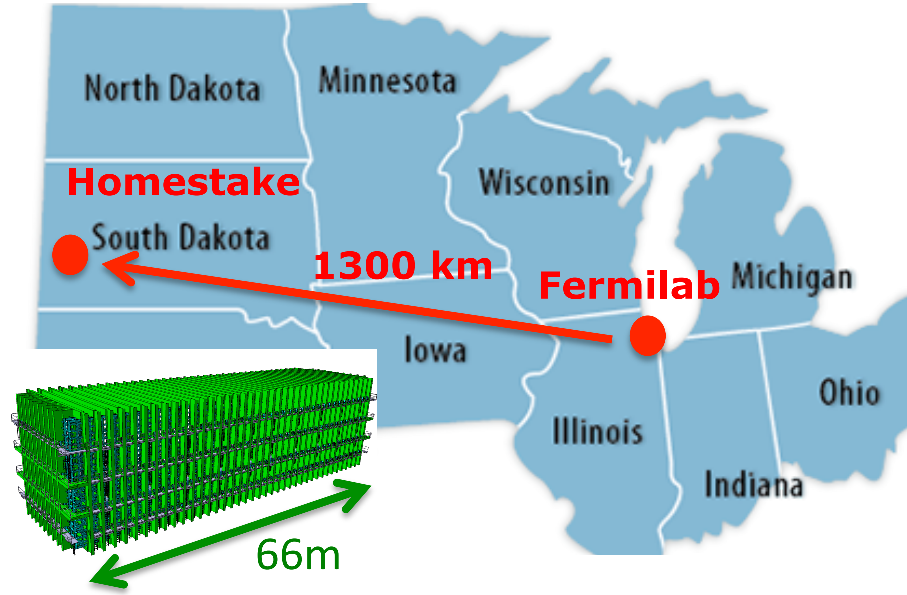
"Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector.

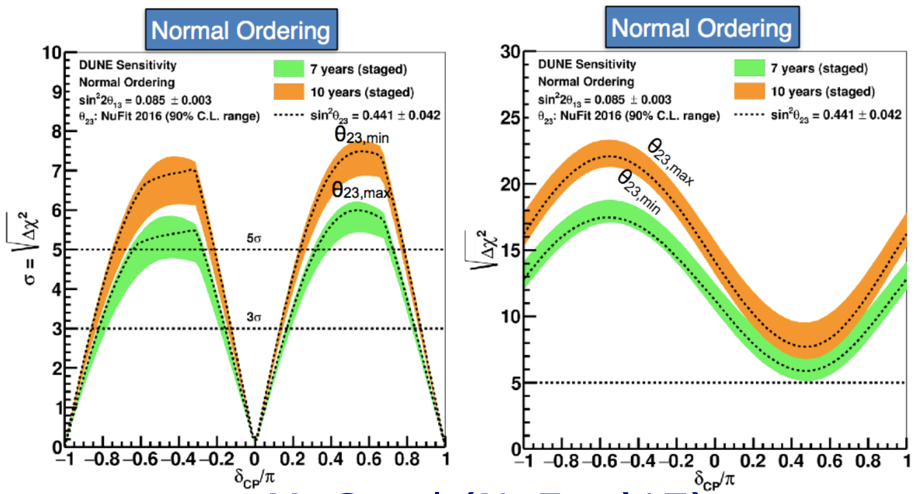
CERN should develop a neutrino programme to pave the way for a substantial role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline projects in USA and Japan".

- Since 2015, significant international effort has focused around two long-baseline projects: DUNE (USA) and Hyper-Kamiokande (Japan).
  - ➢ Both projects are now in their technical design phases.
- CERN has also made a major investment in its Neutrino Platform.

DUNE

- ◆ A long-baseline neutrino experiment from Fermilab to Homestake mine.
  - ➢ Powerful accelerator neutrinos beam produced by a new LBNF facility at Fermilab.
  - ➢ Multi-detector experiment, with 40kt Far Detector based on LAr-TPC technology.
  - ➢ First beam data in mid-2020s.
- ◆ >5σ sensitivity to CP violation over a wide range of δ_{CP} values.
- ◆ 1000+ international collaboration (largest in neutrino physics!)
- ◆ Recent major capital commitment by UK government.



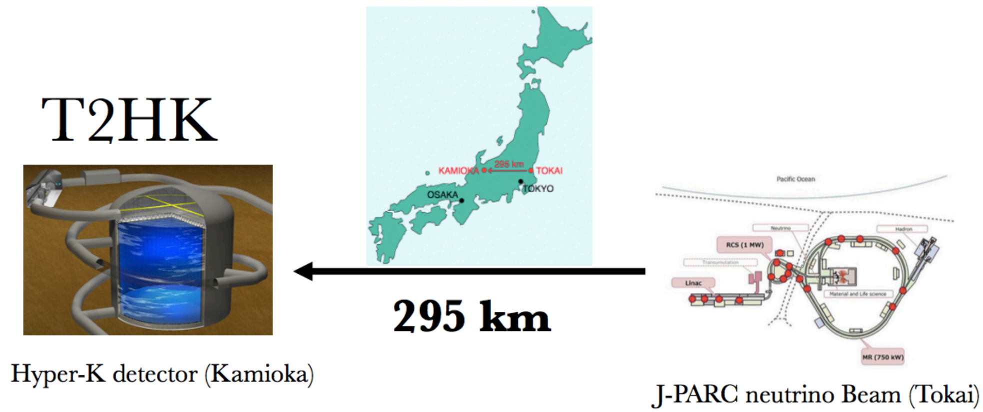


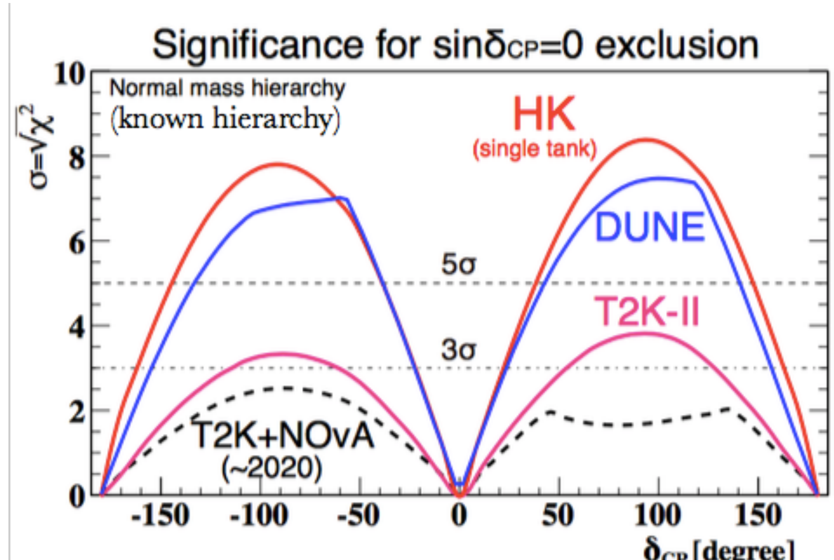
M. Sorel (NuFact'17)

Hyper-Kamiokande

- ◆ Long-baseline neutrino experiment from JPARC to Kamioka.
  - ➢ Major upgrade and scale-up of Super-K and T2K technology.
  - ➢ Upgraded 1MW neutrino beam.
  - ➢ Two Water Cherenkov modules, each with ~200kt fiducial mass (with potential for placing one of the modules in South Korea).
  - ➢ Data-taking from mid-2020s.
- ◆ >5σ sensitivity to CP violation over a wide range of δ_{CP} values.
- ◆ Named by Japanese government among seven top-priority science projects on MEXT roadmap.

E. O'Sullivan (NuFact'17)





CERN Neutrino Platform

- The establishment of a Neutrino Platform at CERN has provided a European centre for research, development and collaboration:

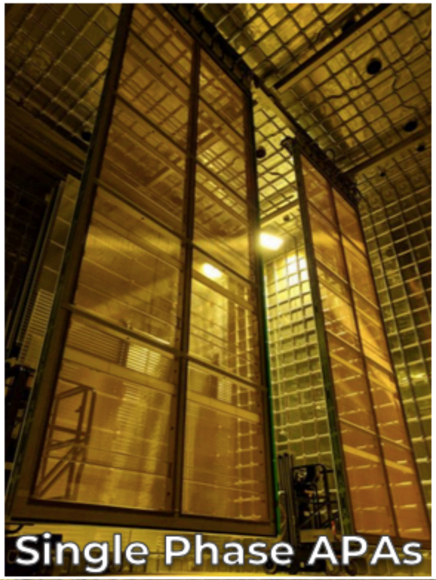
CERN ν Platform Initial Mandate (2015)

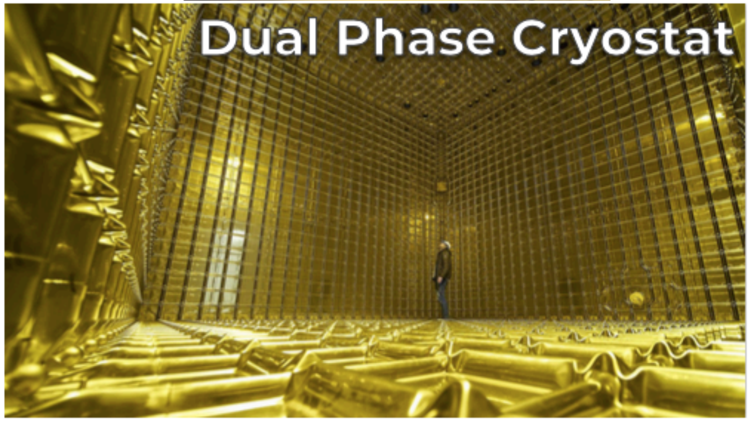
- Assist the various groups in their R&D phase (detectors and components) in the short and medium term and give coherence to a fragmented European Neutrino Community
- Provide the ν community with a test beam infrastructure (charged particles)
- Bring R&D to the level of technology demonstrators in view of major construction activities
- Continue R&D on ν beam, as a possible basis for further collaborations
- Support the short baseline activities (infrastructure & detectors)
- Support the long baselines activities (infrastructure & detectors)
- Be a partner in the physics exploitation

M. Nessi (CERN workshop)

CERN Neutrino Platform

- CERN Neutrino Platform is multi-faceted:
  - ➢ New test-beam facility for a number of detector prototypes, such as the ProtoDUNE's (see right) and the UK's HP-TPC detector.
  - ➢ Near Detector Forum to foster design and development of ND concepts for DUNE and T2K-II / HK.
  - ➢ Neutrino theory working group.
  - ➢ Collaboration on FNAL short-baseline programme, with significant technical effort on SBND and ICARUS.
  - ➢ Expertise in many different areas. But no neutrino beam of its own!
- In addition, CERN has financed the first cryostat for DUNE Far Detector.





A. Kaboth (IOP 2018)

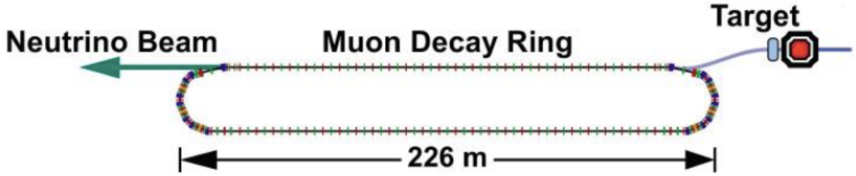
Future Strategy

- Since 2015, the directive of the previous European Strategy Update has largely been implemented:
  - Formation of DUNE and Hyper-K collaborations with the aim of constructing new long-baseline experiments in USA and Japan.
  - Establishment of CERN Neutrino Platform to support these efforts.
- Much of the UK effort has also been focused along these lines.
  - Large UK collaborations within DUNE and Hyper-K projects.
  - Also, significant UK involvement in LAr-based SBN programme at Fermilab, and on Near Detector development for T2K-II / HK.
- If DUNE and Hyper-K remain on track, then the next few years will see their construction and the start of data-taking.
- One future strategy for European involvement in oscillation physics involves consolidating these existing efforts.

Future Strategy

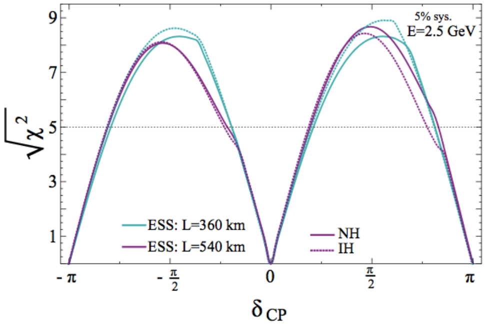
◆ But should Europe have its own accelerator neutrino programme? Here are two proposed projects that could be sited in Europe:

NuSTORM



- Long-standing UK involvement.
- One focus of the recent CERN-led Physics Beyond Colliders study.
- Would deliver an intense neutrino beam from a muon storage ring.
- Capable of precision measurements of neutrino interaction physics, plus searches for short-baseline neutrino oscillations.
- Could be cited at CERN or FNAL.

ESSνSB



- European Spallation Source has been under construction since 2014. (UK listed as a collaborating nation).
- Once complete, the facility could be extended to deliver a conventional neutrino beam (~300 MeV).
- Highly sensitive to CP violation as part of a long-baseline programme.

Questions

- Is Europe (and the UK) pursuing the correct path in collaborating on future long-baseline neutrino projects in the USA and Japan?
  - How could we strengthen the European involvement?
- Should Europe pursue its own accelerator neutrino programme?
  - Could be: big or small, short or long baseline, conventional or other type of beam, based at CERN or elsewhere, etc…
- The current strategy statement (and this talk!) focuses on future accelerator projects, but what about non-accelerator projects?
  - e.g. KM3NeT, PINGU, reactor neutrino programmes, etc…
- How can we improve our understanding of neutrino production and interaction to support precision measurements?
  - Need continued develop of theory, and sufficient data on hadroproduction and neutrino interaction physics.
- Anything else?