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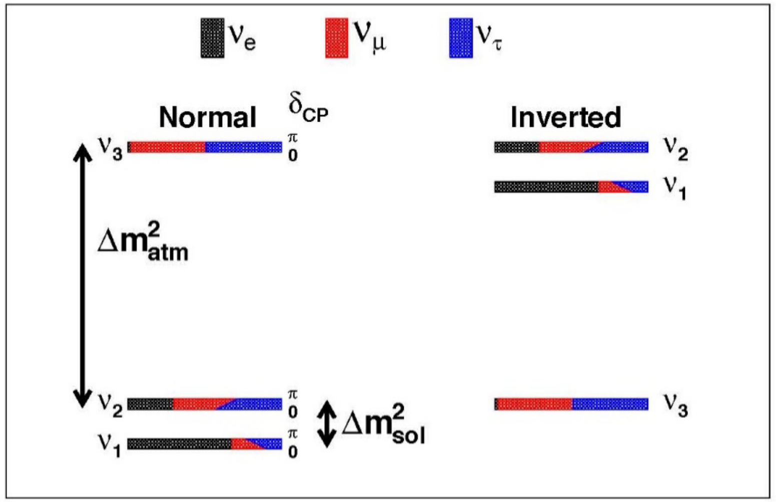
Prospects for the measurement of the neutrino mass ordering and leptonic CP violation

Input ID# 45, 57, 76, 98, 124, 126, 154,158, 167

Open Symposium Update of the European Strategy for Particle Physics, Granada, 13-16 May 2019

Neutrino Mass Ordering (MO, sometimes called MH)



A degree of freedom in neutrino mass spectrum: neutrino masses can be ordered following the generations (normal hierarchy) or not (inverted hierarchy).

Related to

sign of $\Delta m^2_{31}=m_3^2-m_1^2$

One of the key goals in neutrino physics:

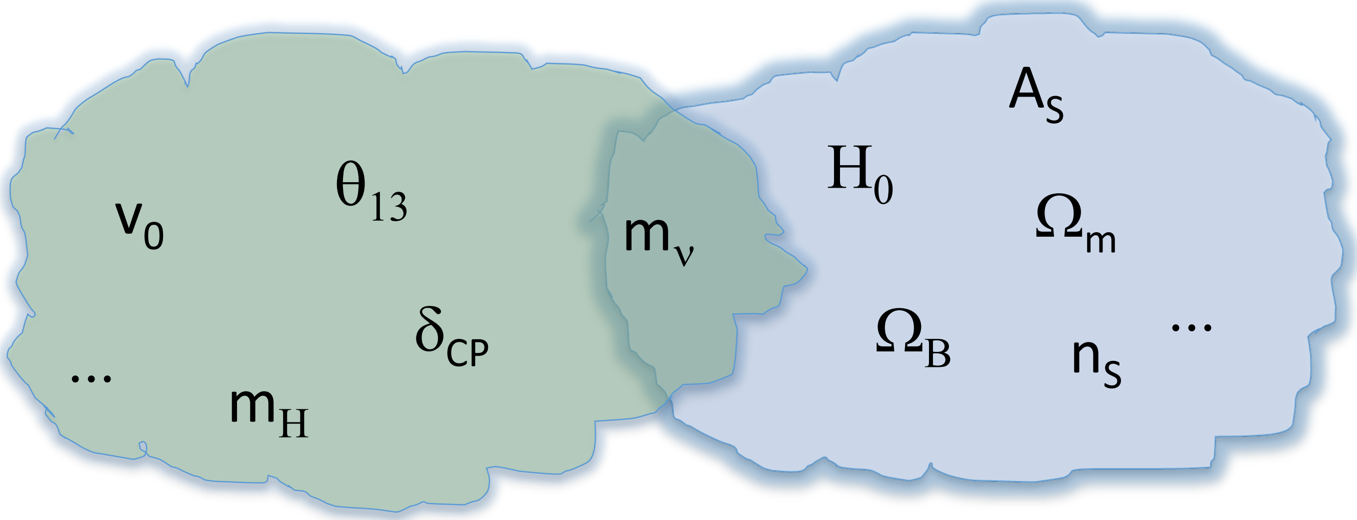
- Neutrino masses can be measured in lab or in cosmo, but to single out the individual masses you need to know MO
- Important phenomenological consequences in neutrino oscillations, supernova neutrinos, cosmology, neutrinoless double beta decays, ...
- Important consequences in neutrino theory: model building, symmetries etc.

The importance of measuring m_ν

Dedicated talk by Susanne Mertens in this session

- The only parameter measurable both by hep and cosmology
- **A crucial test of consistency**

Standard model of particle physics **Standard model of cosmology**

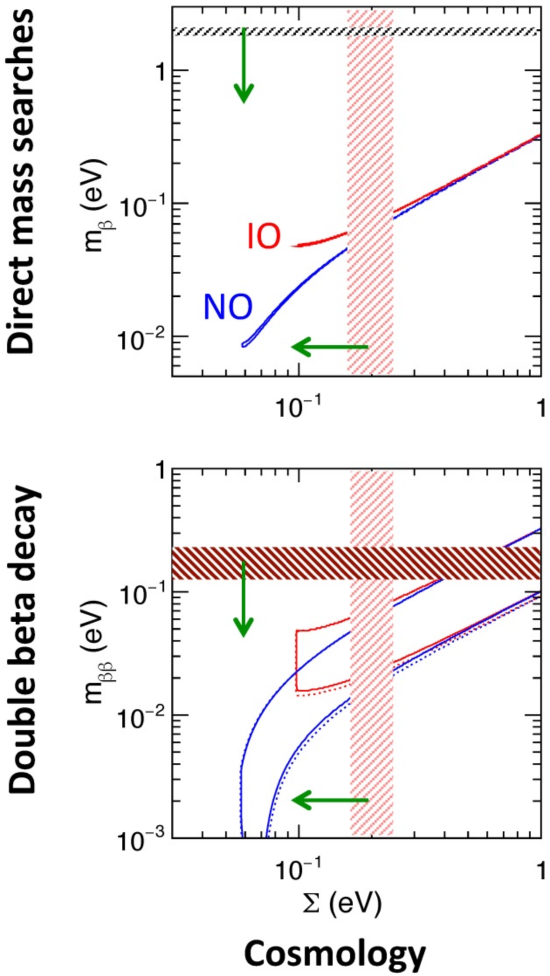


Cosmology measures $\sum_i m_i$

Double beta decay measures $\left|\sum_i U_{ei}^2 m_i\right|$

Direct searches measure $\left(\sum_i |U_{ei}^2| m_i^2\right)^{1/2}$

To compare hep with cosmology, neutrino oscillations parameters must be known, in particular mass ordering (MO)



The importance of measuring δ_{CP}

One of the few unknowns of the Standard Model (together with neutrino masses): a fundamental parameter of nature waiting to be measured

Matter/antimatter asymmetry in the Universe requires CP violation

Jarlskog invariant:

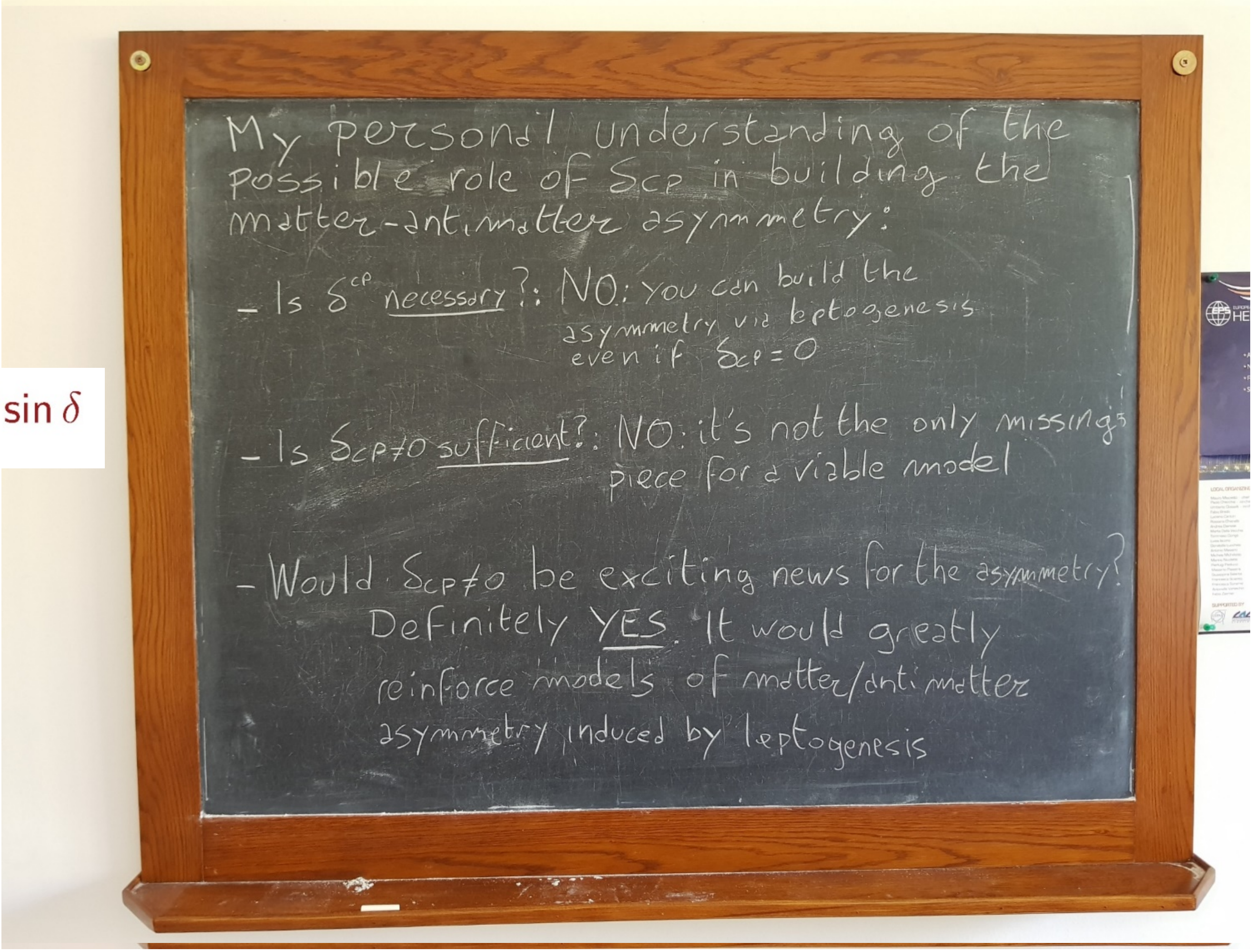
$$J = |\mathrm{Im}(U_{\alpha 1} U^*_{\alpha 2} U^*_{\beta 1} U_{\beta 2})| = s_{12} c_{12} s_{23} c_{23} s_{13} c^2_{13} \sin\delta \equiv J^{\max} \sin\delta$$

$$J^{max}_{\nu} = (3.33 \pm 0.6) \times 10^{-2}$$
$$J^{max}_{quarks} = (3.18 \pm 0.15) \times 10^{-5}$$

Quarks are ruled out, neutrinos not necessarily

Through leptogenesis, theory link the ν −mass generation to the generation of baryon asymmetry of the Universe as suggested by Fukugita and Yanagida already in 1986.

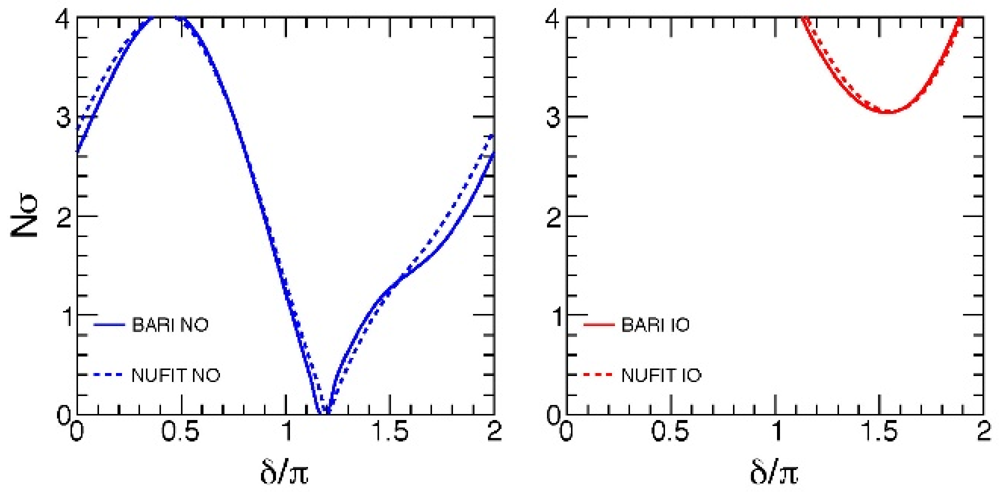
The Dirac phase δ_{CP} can be one of the ingredients of these mechanisms (Silvia Pascoli talk)



Status of CP and MO

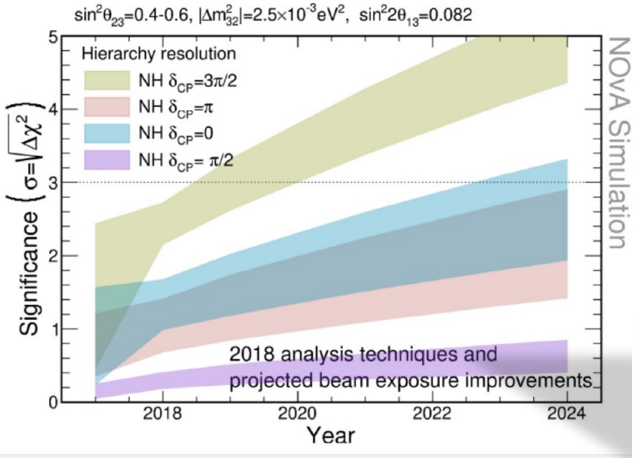
From the previous talk by Eligio Lisi

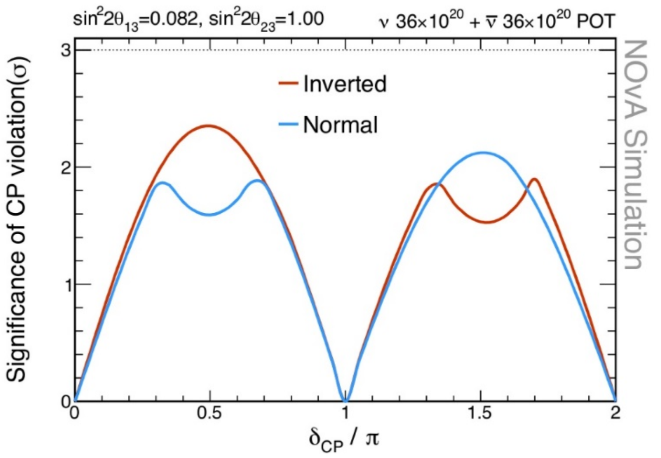
Global fit including accelerator data (T2K and Nova), atmospherics (SK), reactors (Daya Bay, Reno and Double-Chooz) and solars (SNO, SK and Kamland)



- **CP conservation disfavored at 1.5σ** (were 2σ in 2016)
- **NO favored at 3σ** (were 2σ in 2016)

Running experiments sensitivity projection



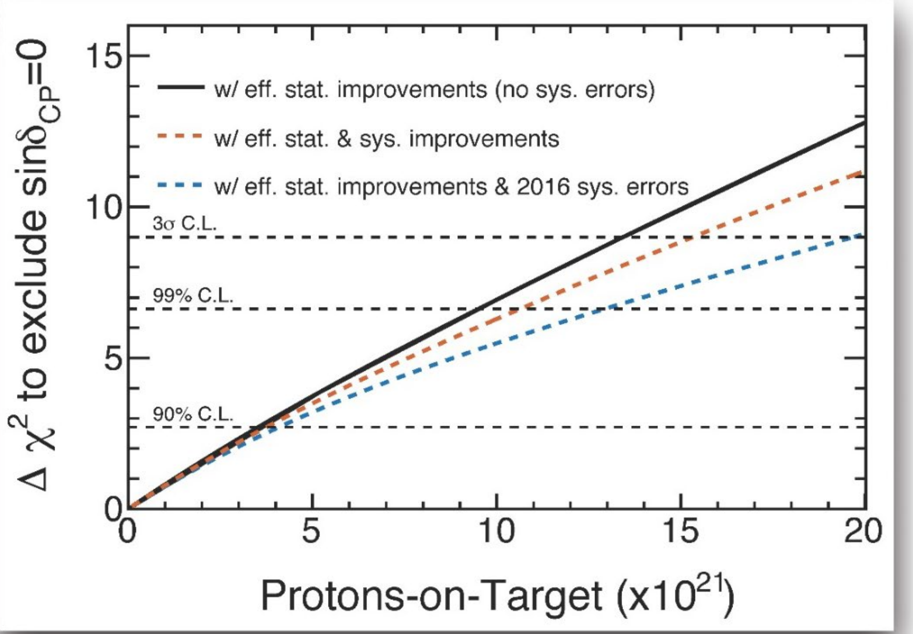


- 3σ sensitivity to MO for favorable parameters by 2020
- 3σ sensitivity for 30-50% (depending on octant) of δ_{CP} range by 2024
- Assuming unknown hierarchy, 2σ sensitivity to CP violation for favorable parameters

T2K-II

Abe et al, 1609.04111

Input ID: #158



- by 2026 (20×10^{21} POT): $>3\sigma$ sensitivity on CP violation

Ways of measuring MO

1) Direct oscillation effects in ν_e-ν_e oscillations (Juno)
2) Different modulations and resonances in matter effects for neutrino oscillations through the Earth (Super-Kamiokande, Ice Cube, Orca, Pingu, Hyper-Kamiokande, Dune)
3) Direct oscillation effects in ν_μ-ν_e oscillations (T2K, Nova, HK, Dune)

To be noted that methods 1) and 2) work because θ_{13} is large.
It's the value of θ_{13} that guides the strategy in measuring MO and CP

Electron neutrino vacuum oscillations

Phys.Lett. B533 (2002) 94-106
Astroparticle Phys.18 (2003) 565-579

$$P_{\bar\nu_e\to\bar\nu_e} = 1 - 2|U_{e3}|^2(1-|U_{e3}|^2)\left(1-\cos\frac{\Delta m^2_{31}L}{2E}\right)$$

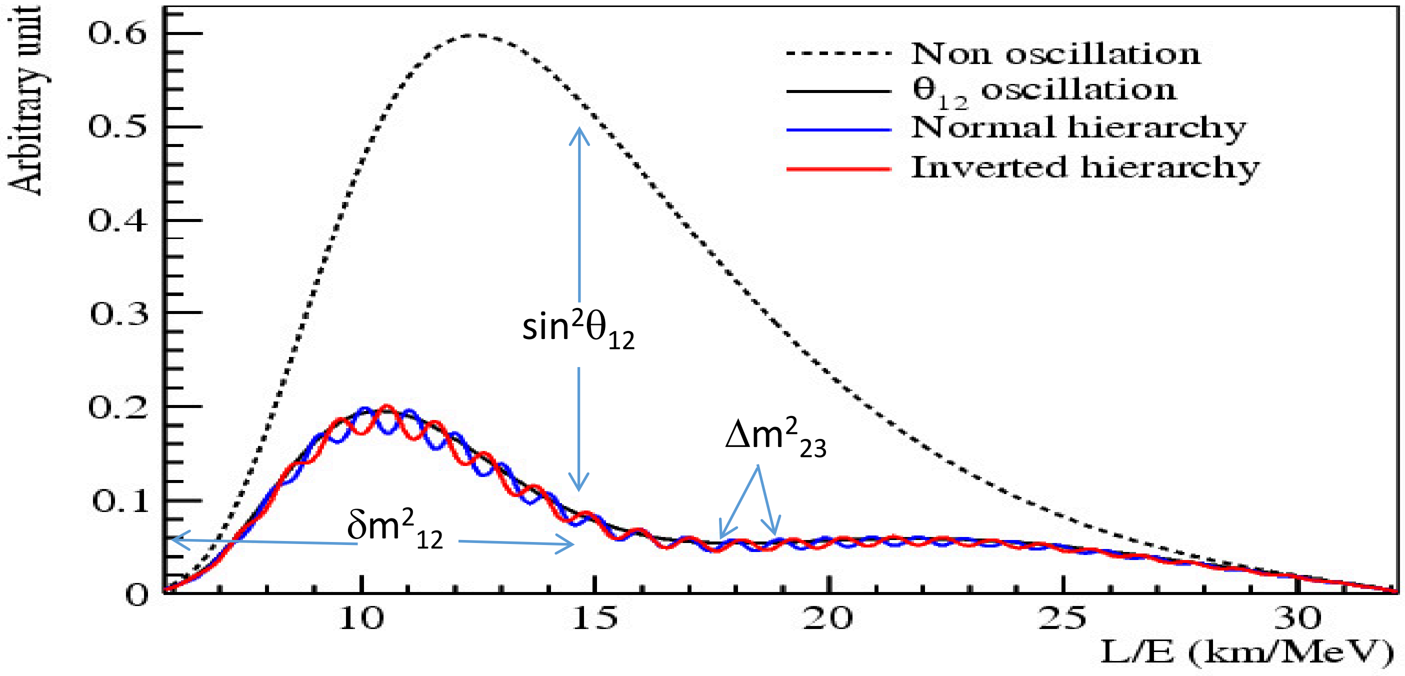
Atmospheric

$$-\frac{1}{2}(1-|U_{e3}|^2)^2\sin^2 2\Theta_{12}\left(1-\cos\frac{\Delta m^2_{21}L}{2E}\right)$$

Solar

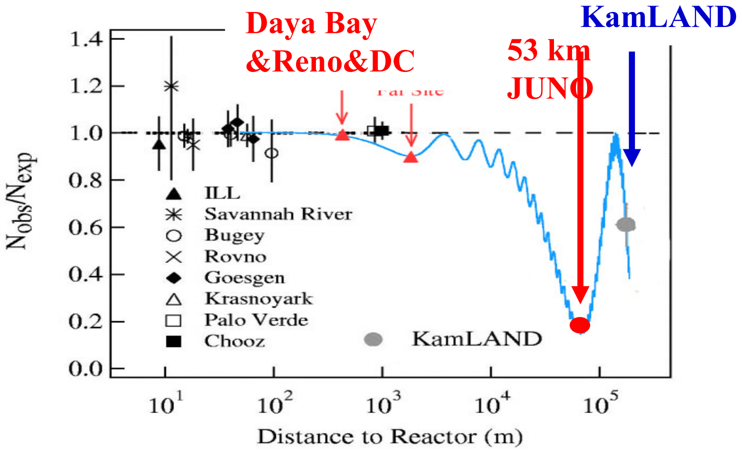
Interference

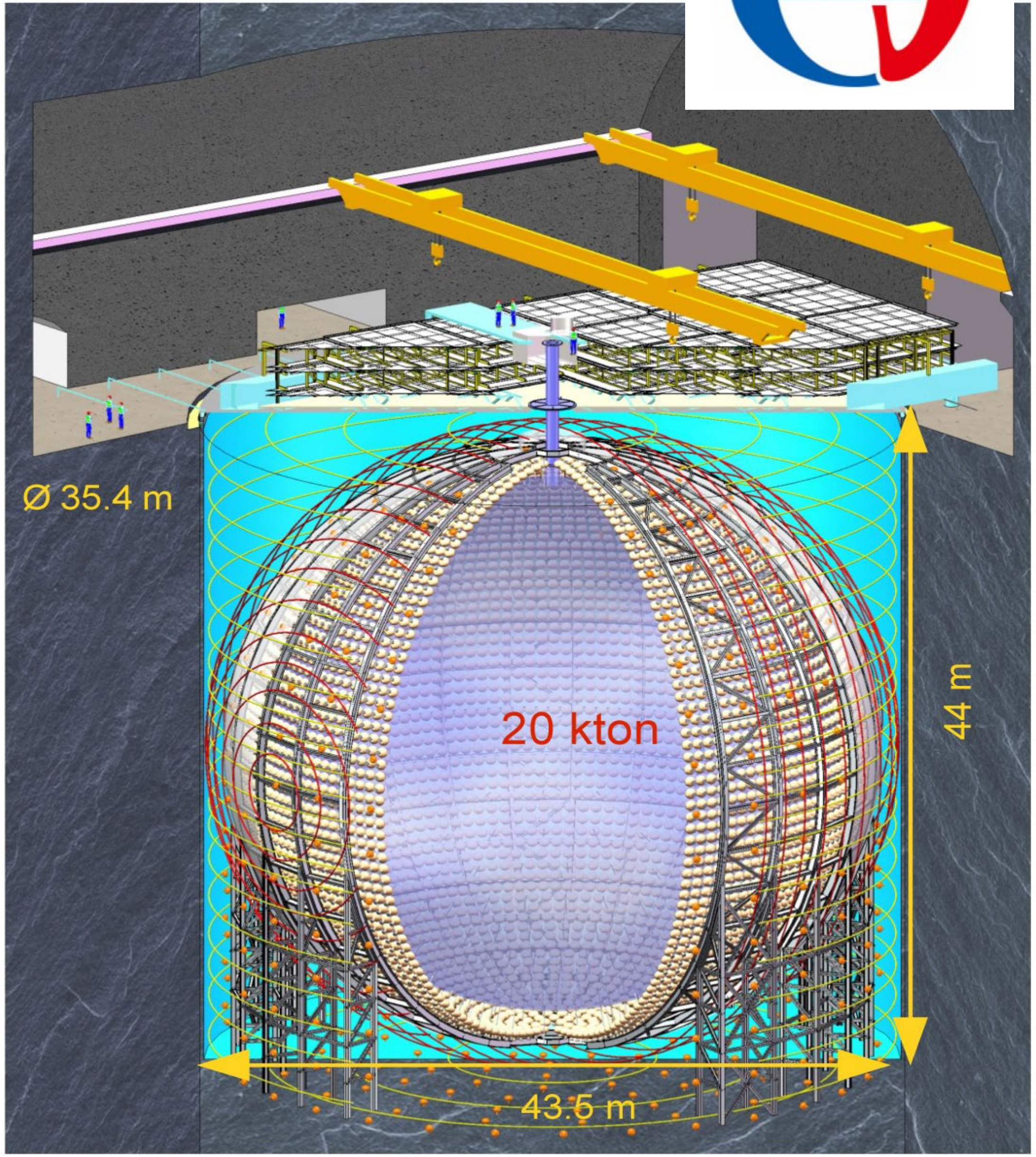
$$+2|U_{e3}|^2(1-|U_{e3}|^2)\sin^2\Theta_{12}\left(\cos\left(\frac{\Delta m^2_{31}L}{2E}-\frac{\Delta m^2_{21}L}{2E}\right)-\cos\frac{\Delta m^2_{31}L}{2E}\right).$$



Juno

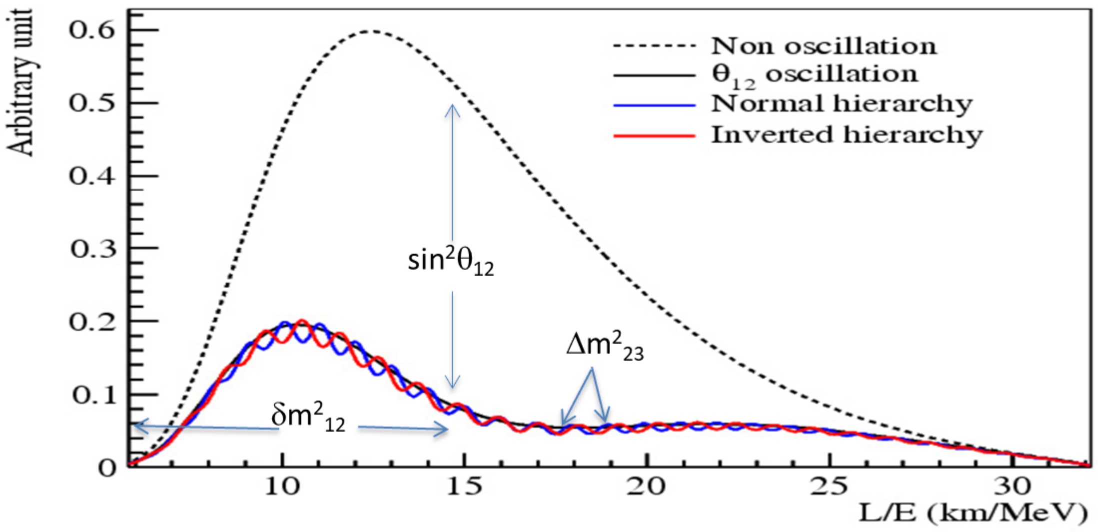
- **Central detector**
  - Acrylic sphere with liquid scintillator
  - PMTs in water buffer
  - 78% PMT coverage
- **Water Cherenkov muon veto**
  - 2000 20" PMTs
  - 35 ktons ultra-pure water
  - Efficiency > 95%
  - Radon control → less than 0.2 Bq/m^3
- **Compensation coils**
  - Earth magnetic field <10%
  - Necessary for 20" PMTs
- **Top tracker**
  - Precision muon tracking
  - 3 plastic scintillator layers
  - Covering half of the top area





Juno

- 3σ MO
- Provided that energy res. <3%
- 4σ with an external input of Δm_{ee}<1%
- Precision measurement of other 3 neutrino osc. parameters
- Supernovae neutrinos
- Geoneutrinos
- Diffuse Supernovae ν's
- Atmos&sol neutrinos
- Nucleon Decay
- Exotic searches
- Maybe 0ββν



	Δm^2_{21}	$\sin^2\theta_{12}$	$\|\Delta m^2_{31}\|$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant experiment	KamLAND	SNO	T2K & NOvA /Daya Bay	Daya Bay	T2K
Individual 1σ	2.4%	6.7%	3.2%/3.5%	4.0%	9.8%
Global 1σ *	2.2%	3.9%	1.2%	3.4%	5%
JUNO expected 1σ	0.6%	0.7%	0.4%	~15%	-

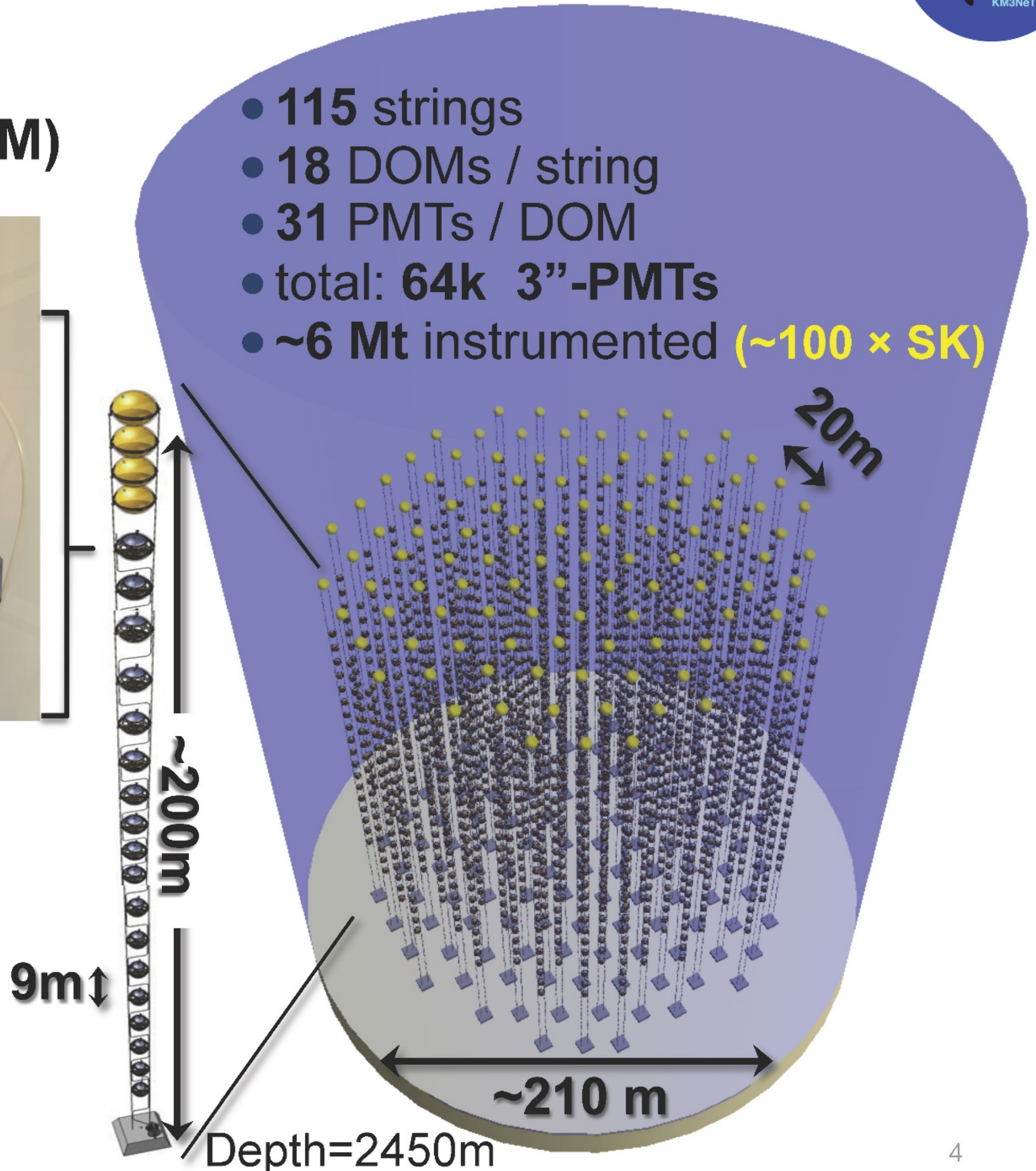
ORCA (Oscillation Research with Cosmics in the Abyss)

J.Phys G43 (2016) n.8, 084001

Digital Optical Module (DOM)

31 x 3”-PMTs
(19↓, 12↑)

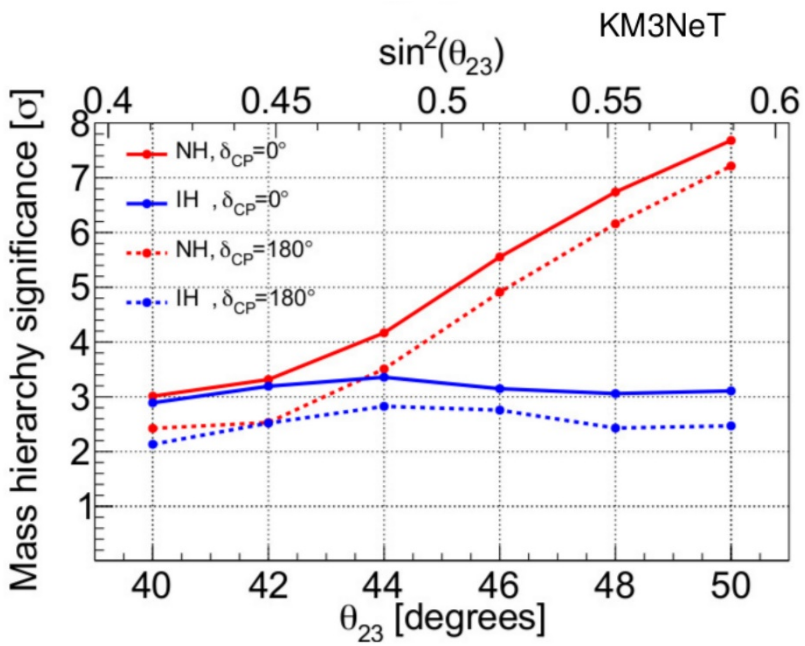
- Uniform angular coverage
- Directional information
- Single photon counting



Measuring MO with ORCA

J.Phys G43 (2016) n.8, 084001 but see also Capozzi, Lisi, Marrone J.Phys. G45 (2018) no.2, 024003

Sensitivity after 3 years of data taking



Aimed to take data by 2022 (but not yet fully funded)

Could be improved by firing a neutrino beam from Protvino (P2O) (which requires a major upgrade of the Protvino 70 GeV SPS), see arXiv:1902.06083 and Input ID # 142

P2O could measure CP violation in a sensitive way only if the far detector could have a 0.5 GeV threshold in neutrino detection. This requires a detector with a 10 times denser instrumentation

PINGU is a possible IceCube extension with similar performances of ORCA

Measuring CP violation

- Not the most elegant or compact parametrization
- But all the contributions are explicit

$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right] \quad \theta_{13}\ \text{dri}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{CPe}$$

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta\} \sin^2 \frac{\Delta m_{12}^2 L}{4E} \quad \text{solar drive}$$

$$\mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) \quad \text{matter effect (CP odd)}$$

- All the oscillation parameters matter
- Synergy between different experiments necessary

Third generation Long Baseline Experiments

Two big projects underway:

DUNE in the States. Long (1300 km) baseline and on-axis neutrino beam.
Matter effects are large (big sensitivity on MO), all the neutrino interaction modes contribute (quasi-elastic, resonances, deep-inelastic).
The Liquid Argon far detectors can precisely reconstruct the event energy for all the topologies

HyperK in Japan. Short (295 km) baseline and off-axis neutrino beam.
Matter effects are small (optimized for CP), neutrino interaction are mostly quasi-elastic.
The water Cherenkov far detector can precisely reconstruct quasi-elastics and is very massive.

Improving the already remarkable synergy between T2K and Nova

Great complementarity also in many astrophysics measurements (SN, relic SN, solar and atmospheric neutrinos, indirect DM searches etc.) and **proton decay** (see also next slides)

Hyper-Kamiokande

Input ID: #158, Design Report: arXiv:1805.04163

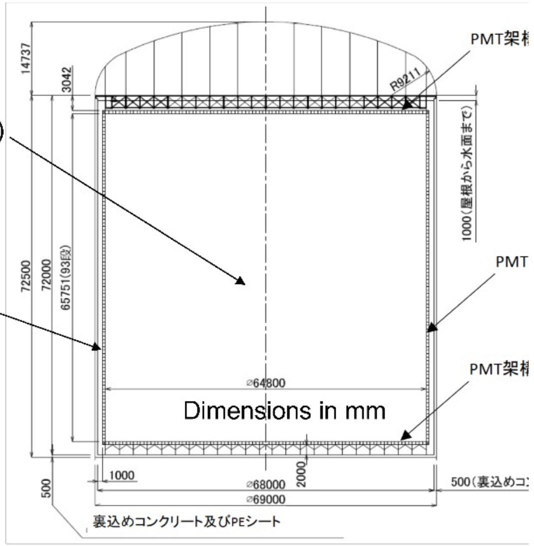
- A 260kt tank of pure water
- Inner Detector 216kt (fiducial volume ~200kt)

Between 20% and 40% photosensor coverage

- Outer Detector veto region

Barrel region 1m thick, endcaps 2m thick
15,000 3" PMTs with wavelength-shifting plates

- Front-end electronics inside tank



Input ID: #76

Gigantic neutrino and nucleon decay detector

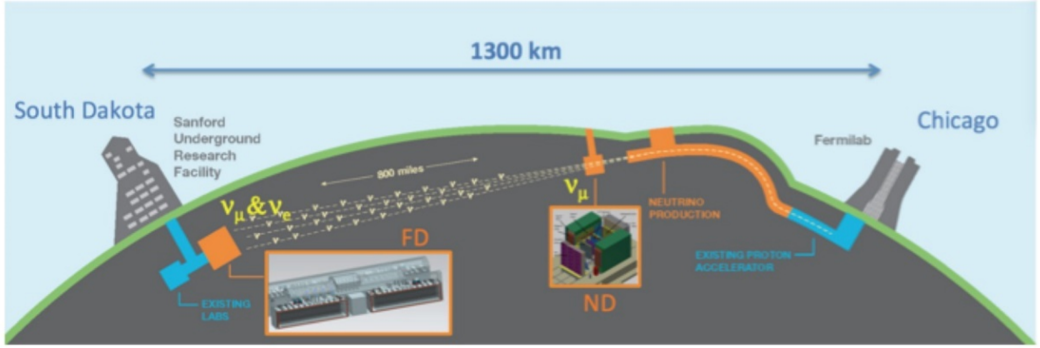
- 186 kton fiducial mass: ≈ 10 x Super-K
- x2 higher photon sensitivity than Super-K
- Super detector capability, technology still evolving (i.e. gadolinium loading)
- 2nd oscillation maximum by 2nd tank in Korea (T2KK) under study, PTEP (2018) 6,063C01

MW-class neutrino beam by upgraded J-PARC (1.3 MW)

Close detector system upgrades

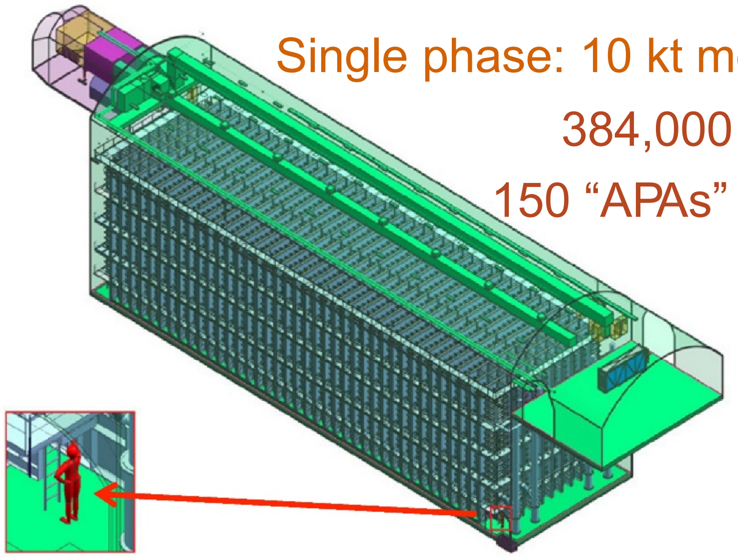
- ND280 refurbishing (already for T2K-II)
- Intermediate distance water Cherenkov detector under study

2018 - Japanese seed-funding and U.Tokyo commitment to 2020 start, Hyper-K ready by 2027



Input ID: #126, #167. CDR: arXiv 1601.05471. TDR this year

- 1.2 MW (up to 2.4 MW) neutrino beam from Fermilab 120 GeV Main Injector
- 4 x10-kt (fiducial) liquid argon TPC modules
- Single- and dual-phase detector designs (1st will be single phase)
- Integrated photon detection
- Close detector CDR end of this year
- 2019 - Start main cavern excavation in South Dakota;
- 2022 - Start installation of first far detector module;
- 2026 - Beam operation starts with first two detector modules.



Single phase: 10 kt module

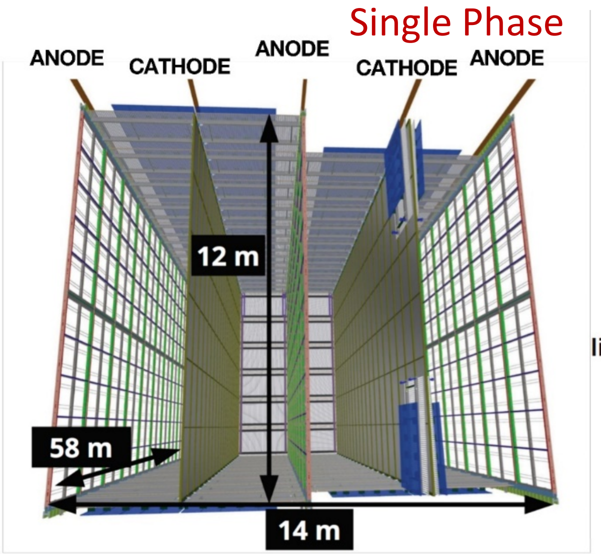
384,000 readout wires

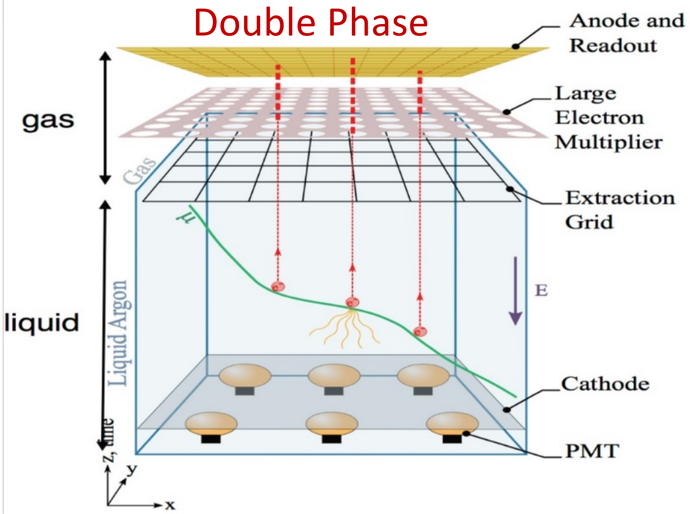
150 “APAs” (2.3 m x 6 m)

12 m high

15.5 m wide

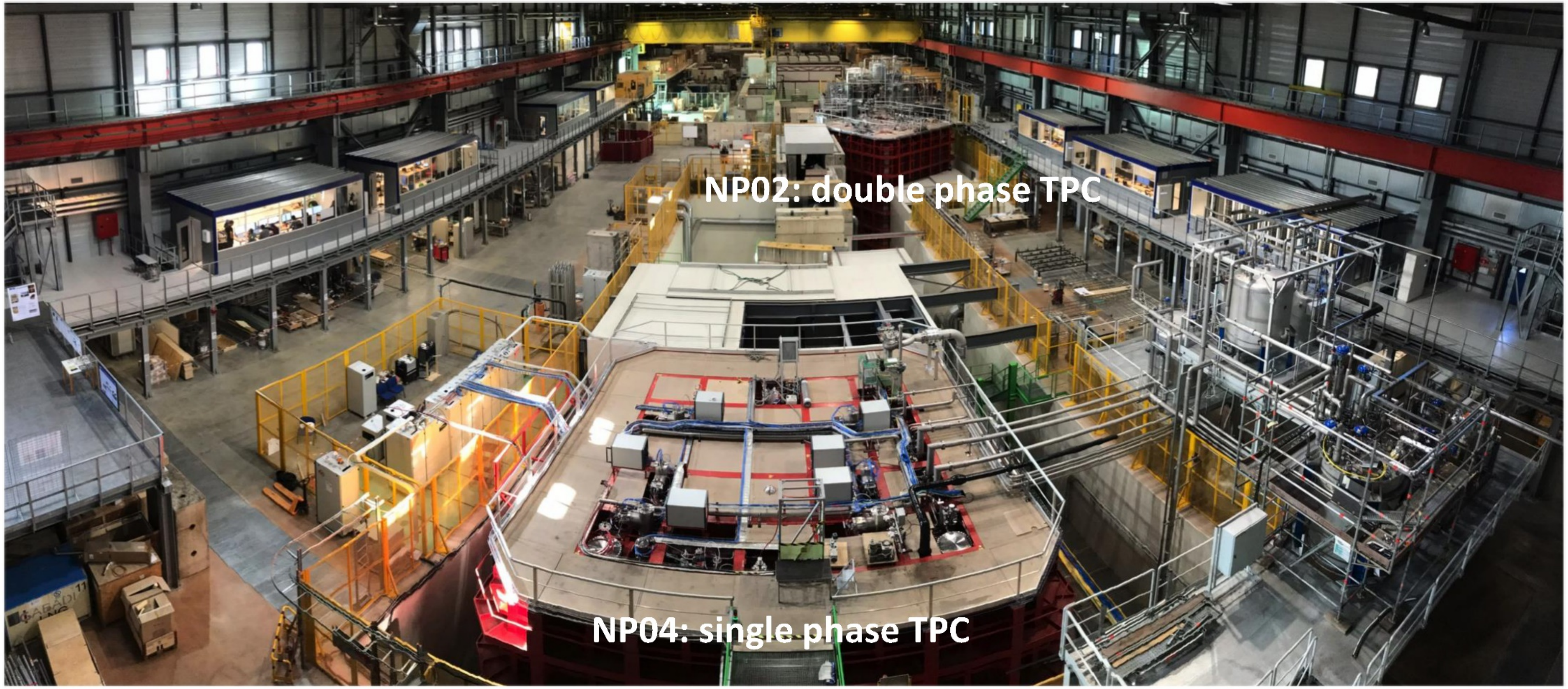
58 m long





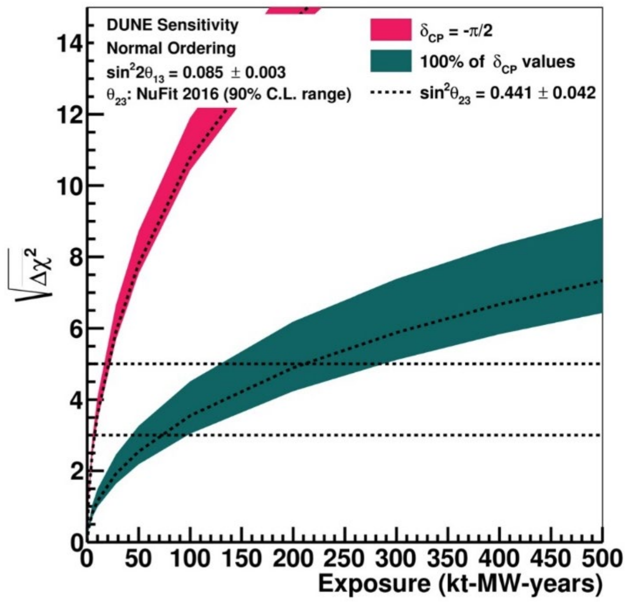
Neutrino Platform

Paving the way … at best.
So far 146 institutions in the 8 projects, among which Lar demonstrators, babyMIND, T2K close detector upgrade, Enubet.
Spectacular results with the LAr single phase TPC demonstrator (protoDUNE)

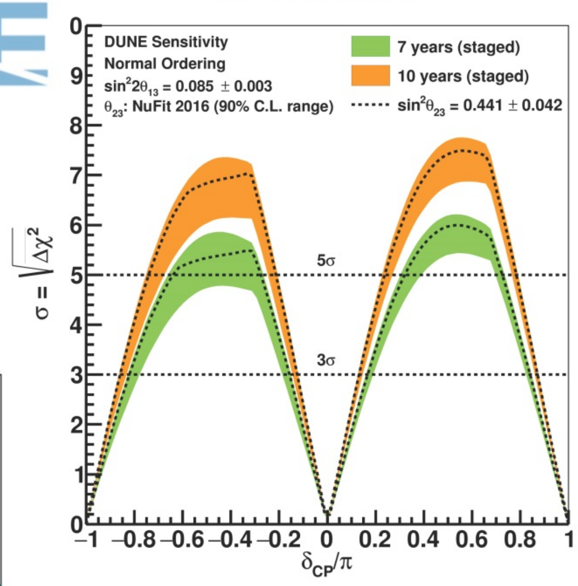


Dune and HK MO and CP Sensitivity

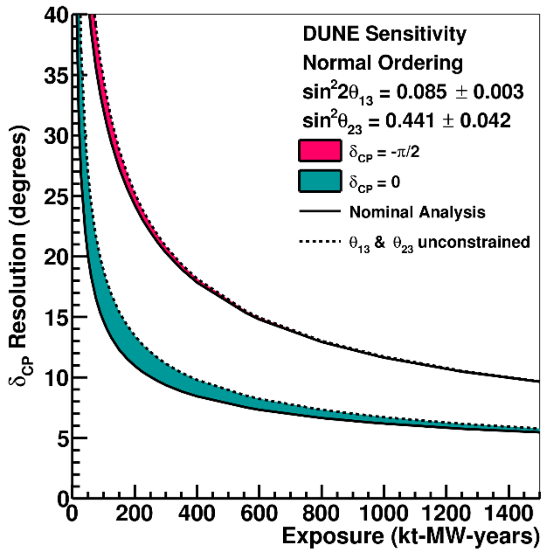
MO Sensitivity



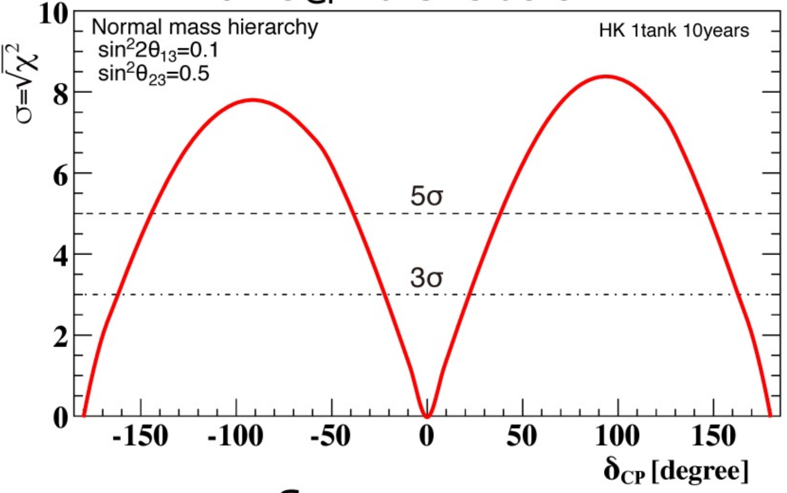
CP Violation



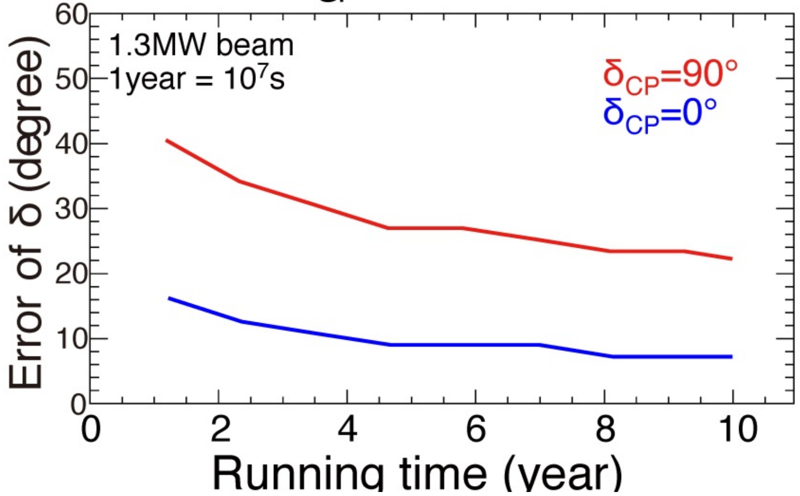
δ_{CP} Resolution



$\sin\delta_{CP}=0$ exclusion



δ_{CP} 1σ error



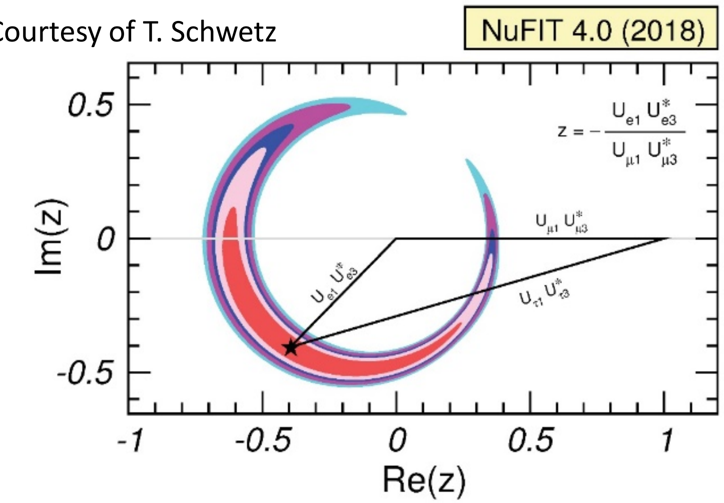
Can next gen experiments look for new physics?

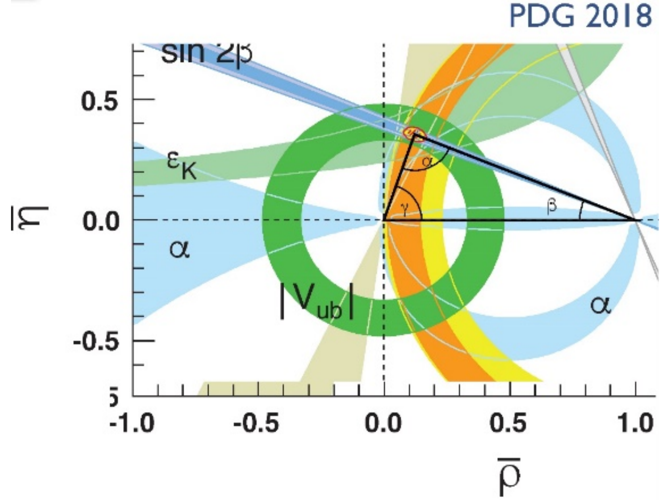
*"There are two possible outcomes: if the result confirms the hypothesis then you've made a **measurement**. If the result is contrary to the hypothesis then you've made a **discovery**", **Enrico Fermi**.*

Definitely YES, but we don't have many guidelines by theory. So it's difficult to quantify the reaches, compare experiments and define strategies

Sterile neutrinos are covered by B. Fleming talk
Searches of heavy neutral leptons are covered by N. Serra talk

Courtesy of T. Schwetz



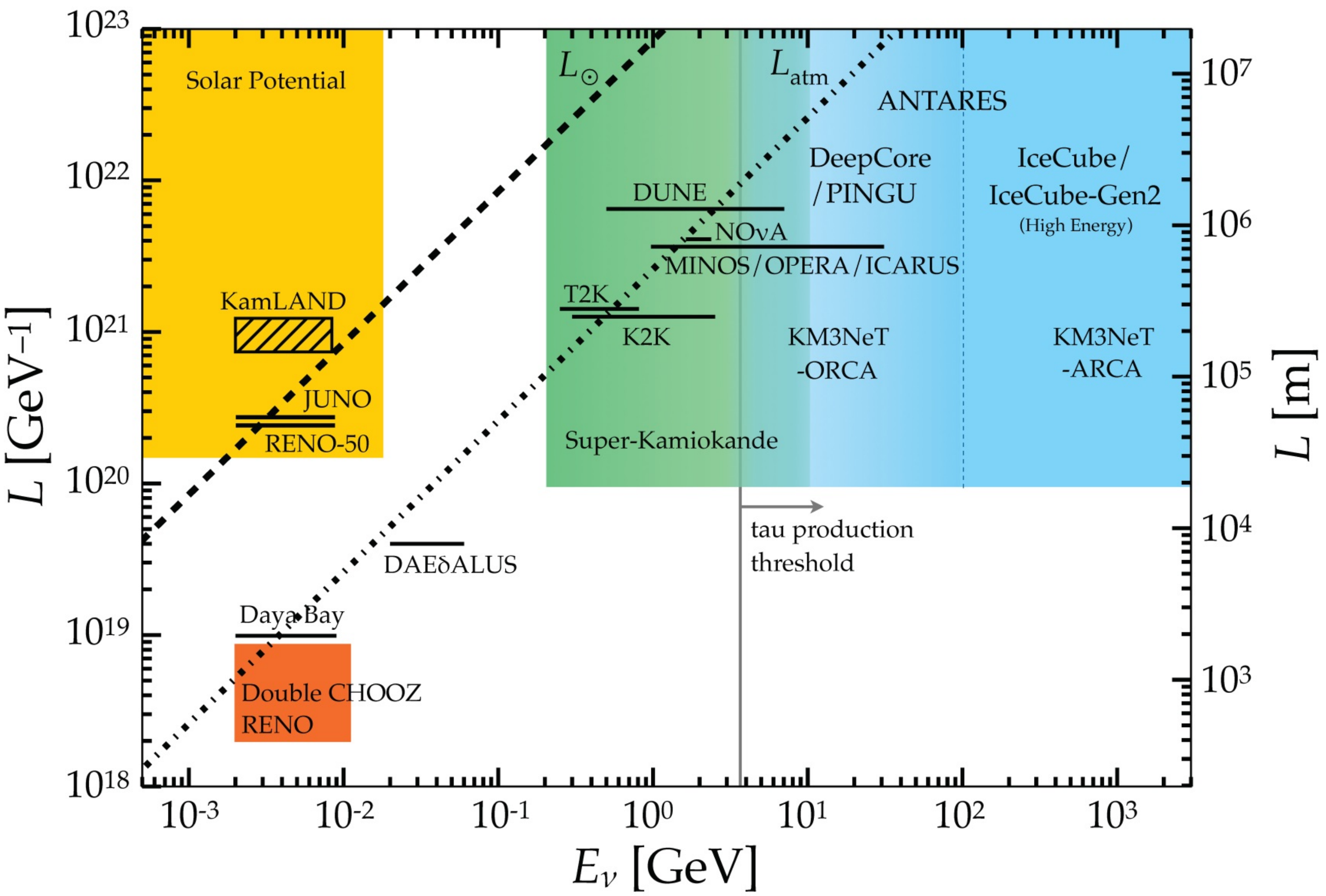


Pragmatically:

- Directly look for nonstandard neutrino interactions (NSI) in the detectors
- Overconstrain three-neutrino oscillations and look for inconsistencies
- Test L/E scaling

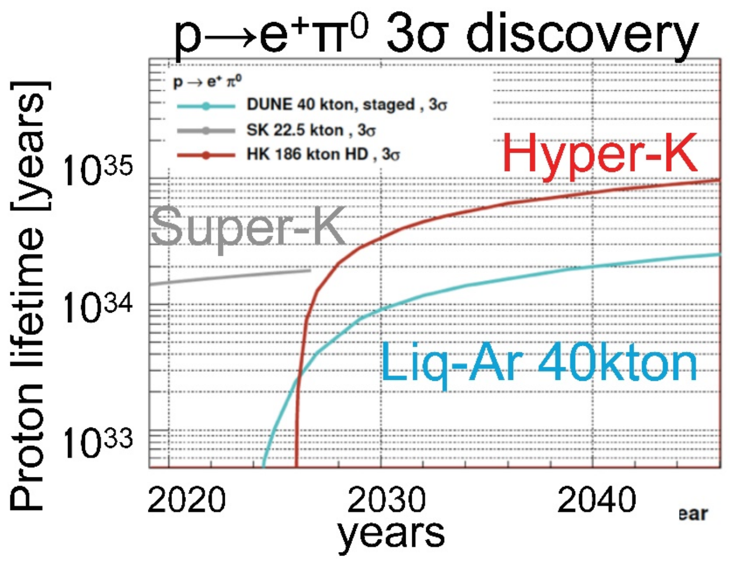
Complementarity: same L/E but different E

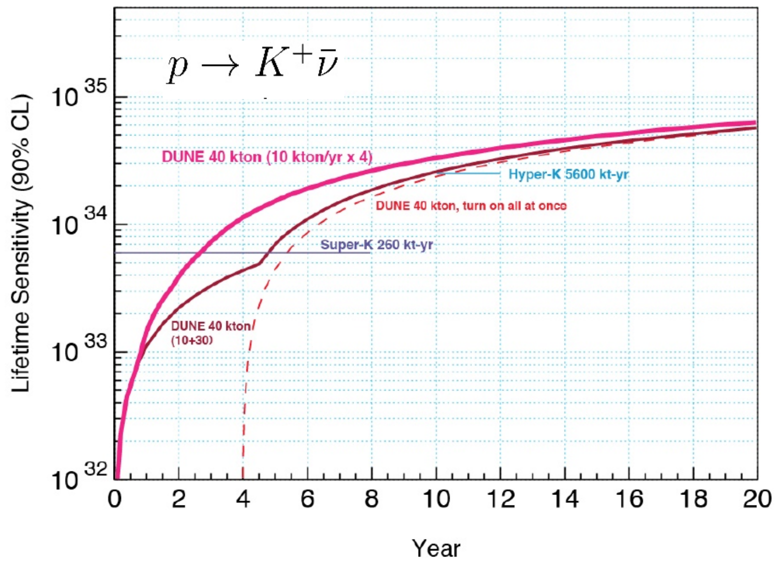
Any subleading non-oscillatory effect would violate L/E scaling.
Atmospheric/astrophysical neutrinos play a very important role (F. Halzen talk in this session)



Complementarity

- Complementarity will increase the discovery potential of next generation experiments.
- HK and Dune nicely complement their physics reach in neutrino oscillations (see f.i. arXiv:1501.03918)
- Juno can improve their sensitivity in precisely measuring solar parameters while HK and Dune can measure Δm_{ee}^2 for Juno
- The three liquids (water, argon and scintillator) really complement each other in detecting **proton decays** (pushing the sensitivity beyond 10^{35} years), SuperNovae neutrinos, solar neutrinos, indirect DM searches, low energy neutrino astronomy.



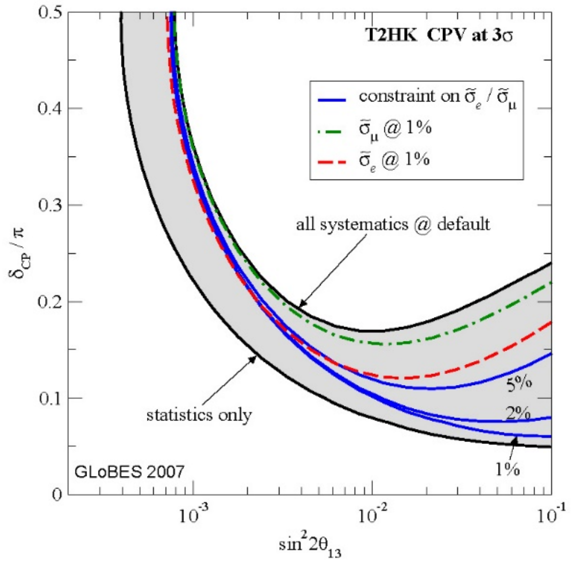


Systematic errors

Discussed in detail in the next talk by F. Sanchez

... not a surprise:
Huber, MM, Schwetz,
JHEP 0803 (2008) 021

The physics potential of Dune and HK will be ultimately limited by systematic errors.



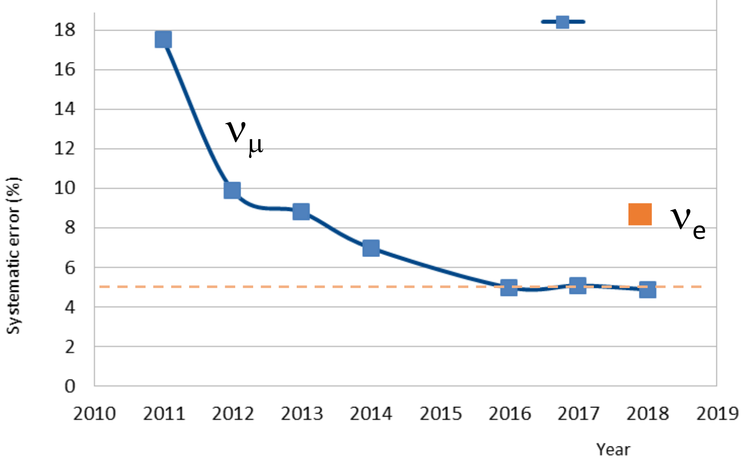
They come from:

- Insufficient knowledge of initial neutrino fluxes
- Insufficient knowledge of neutrino cross sections
- Measurements of efficiencies in signal detection and background rejection

They can be mitigated by:

- Dedicated hadroproduction experiments (see Input ID #45).
- Better and better close detectors
- New dedicated project for neutrino cross sections like
  - Nustorm (Input ID: # 154)
  - Enubet (Input ID: # 57)

T2K Systematics learning curve



What Next

At full statistics Dune and HK will have a 3% statistical error and will be dominated by systematic errors.

Any further generation will require innovative setups

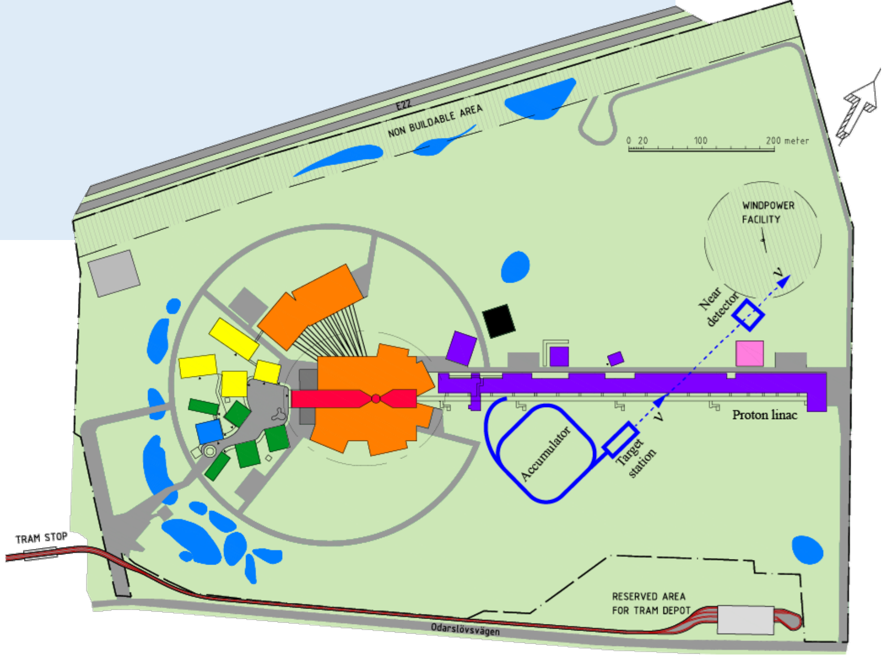
The focus of next to next generation of Long Baseline experiments are new concepts in neutrino beams.

I will briefly mention two possibilities

- Go to second oscillation maximum where CP effects are larger (but pay a factor 3 in neutrino rates): T2HK, ESSνSB, SuperOrca.
- Change neutrino parents: from secondary pions to primary muons: **Neutrino Factories**. In this way initial neutrino fluxes uncertainties are almost cancelled

Input ID: #98

ESS NEUTRINO SUPER BEAM



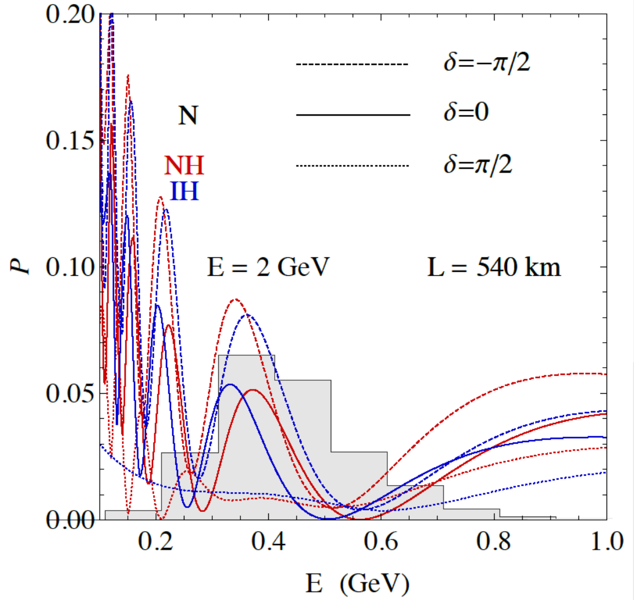
- The ESSnuSB project proposes to add on the European Spallation Source under construction in Lund (Sweden) a Super Beam neutrino facility devoted to the discovery of a leptonic CP violation. The main characteristics of this facility are:
    - 5 MW/2.5 GeV protons,
    - accumulation ring of Ø400 m,
    - 4 target/horn system, 25 m decay tunnel,
    - near detector, far megaton water Cherenkov detector.
- This facility will be operated at the second neutrino oscillation maximum.
- A copious number of muons (>10^{20}/year) can also be produced which could be used for studies of muon ionisation cooling for a future Neutrino Factory or a muon collider. **Very strong synergy with ESSνSB**.
- The far megaton water Cherenkov detector has a rich astrophysical program by detecting cosmological neutrinos. It can also be used to study proton lifetime.

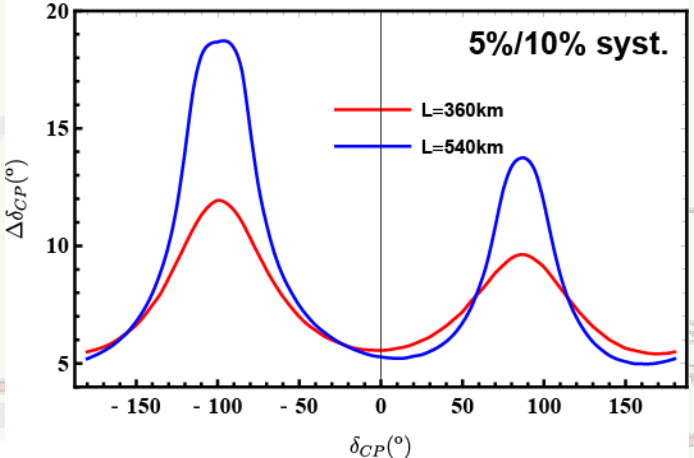
Two European Projets to support ESSnuSB:

- COST: EuroNuNet, 3rd year (2016-2020)
    - *Combining forces for a novel European facilit for neutrino-antineutrino symmetry violation discovery*
    - 13 country members
- ESSnuSB: H2020 DS, 4.7 M€ (3 M€ by EU)
    - 17 institutes including ESS and CERN
    - Approved in August 2017
    - Started beginning of January 2018
    - Duration: 4 years (2018-2021)
    - 5 Work Packages

ESSnuSB performance

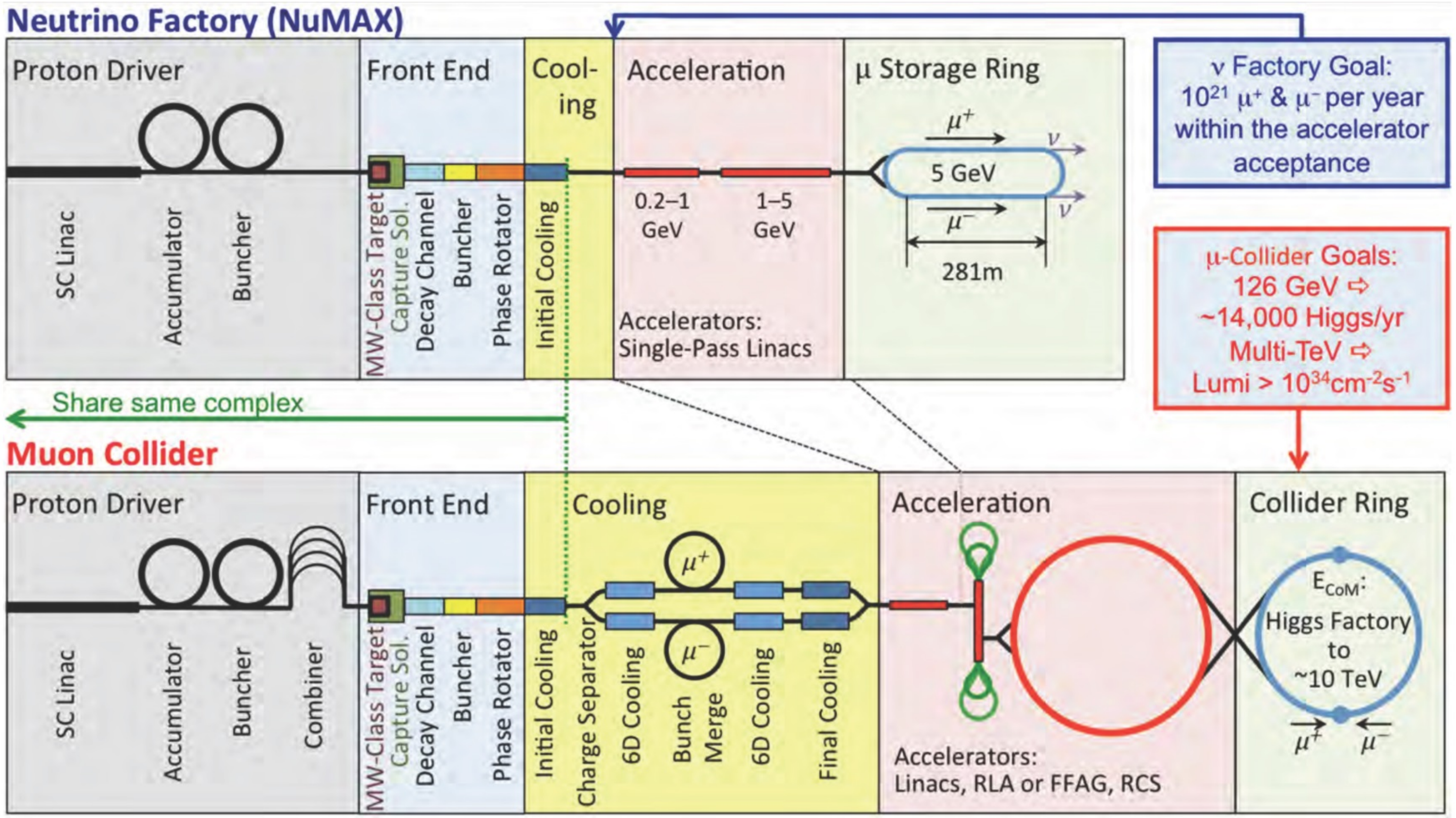
- Excellent coverage of the second oscillation maximum (more sensitivity to δ_{CP} and less influence from systematic errors).
- More than 60% coverage of CP violation parameter δ_{CP}.
- δ_{CP} accuracy:
  - ~5º around 0º and 180º (discovery power)
  - ~10º/12º around 90º/-90 (worst position, precision power)
- Two candidate active mines:
  - Garpenberg (540 km)
  - Zinkgruvan (360 km)





Short term goals
- Complete the CDR by 2021
- Have the preparatory phase funded
- TDR ready by 2024

Neutrino Factory



- ν parents (μ) have all the same energy, same direction and are well counted
- ν beam known at % level (before any close detector constrain)
- Signal events are wrong sign muons
- Proton driver could be ESS
- The first stage of a Muon Collider …
- … but still very expensive (and challenging)

My personal conclusions

- In the previous strategy neutrino physics was the 4th of the 4 main goals:

"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 European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan*."

- … but oscillation experiments had been delocalized in USA and Asia
- In the meantime progress in the field had been faster than "rapid" convincing a growing community of physicists and the funding agencies to invest in future experiments
- The CERN Neutrino Platform had been a very successful realization, its support should be secured and reinforced.
- New projects need the support of CERN accelerator experts
- Complementarity and redundancy are necessary to strengthen the foreseen measurements and allow for unexpected discoveries.
- Furthermore new experiments will provide powerful BSM searches like proton decays ($\tau_p > 10^{35}$ yr) and address several important astrophysical topics.
- In the long term new technologies will be needed, particularly the development of new neutrino beams technologies

Additional slides

Timescales of the submitted inputs

P2O (Input # 142)
Possible time line
The following timeline depends largely on the availability of funds for the individual steps.

- 2018 Construction start of the ORCA detector (already partly nanced)
- 2019-2022 P2O design study
- 2022 Completion of ORCA detector
- 2022-2026 Neutrino beam line construction and accelerator upgrade to 90kW
- 2027-2032 P2O \phase 1" data taking with ORCA
- 2027-2035 accelerator upgrade to 450kW (initially in parallel to running at 90kW)
- 2030-2035 Super-ORCA construction
- 2035 Start data taking of \P2O phase 2" with Super-ORCA

Dune (Input # 126)
LBNF and DUNE have been working towards three international project milestones:
• 2019 - Start main cavern excavation in South Dakota;
• 2022 - Start installation of first far detector module;
• 2026 - Beam operation starts with first two detector modules.
It is expected that these dates will be adjusted when the project baseline is defined. The key
milestones to reach baseline status are:
• 2018/2019 - Collect data with both ProtoDUNE detectors.
• April 2019 - Submit TDR for far detector modules.
• July 2019 - Complete LBNC and Neutrino Cost Group (NCG) review of TDR.
• September 2019 - Present TDR to Resources Review Board (RRB).
• October 2019 - Conduct conceptual design (DOE CD-2a/3b) review of LBNF and the DOE
scope of the DUNE far detector.
The TDR for the near detector is expected to

J-PARC, # 76

JFY	2017	2018	2019	2020	2021	2022	2023	2024
Event	New buildings		HD target		Long shutdown			
FX power [kW] SX power [kW]	475 50	>480 50	>480 50	>480 70		>700 > 80	800 > 80	900 > 80
Cycle time of main magnet PS New magnet PS	2.48 s	2.48 s Mass production installation/test	2.48s	2.48s		1.32 s	<1.32s	<1.32s
High gradient rf system 2nd harmonic rf system		Manufacture, installation/test						
Ring collimators	Add.collimators (2 kW)				Add.colli. (3.5kW)			
Injection system FX system	Kicker PS improvement, Septa manufacture /test Kicker PS improvement, FX septa manufacture /test							
SX collimator / Local shields						Local shields		
Ti ducts and SX devices with Ti chamber	Ti-ESS-1	(Ti-ESS-2)						

Figure 4: Mid-term plan of the MR beam power as of 2018.

NuStorm, #154

2 Time-line

The recent efforts to examine the possibility of siting nuSTORM at CERN represent a preliminary fea- sibility study on limited resources. If the initiative was to be taken further, one might envisage a suitably resourced feasibility study towards a conceptual design report (CDR) over a two-year time-frame. Of note is the considerable work that has already been performed on the concept. The goal of this CDR phase would be to deliver detailed designs and specifications for all key packages. Namely:

- Extraction and beam-line;
- Target/horn and target complex and secondary particle transport;
- Muon decay ring and beam-line elements, in particular the magnets; full simulation of beam dy- namics in the capture, transport and storage ring would need to be performed; finalise ring optics and layout;
- Complete civil engineering evaluation; and
- Detailed costing.

The further development of the project after the CDR phase is sketched in table 1.

Table 1: Outline of a possible nuSTORM time-line.

Year	Objective
0 – 2	Detailed designs and specifications Finalise ring optics and layout Preliminary infrastructure integration & CE designs Preliminary cost estimates and schedule
End 2	Delivery of Conceptual Design Report
3 – 4	Continued design studies and prototyping of key technology
End 4	Approval to go ahead with TDR
5 – 6	Engineering design studies towards TDR Specification towards production CE pre-construction activities
7	TDR delivery
8	Seek approval
8+	Tender, component production, CE contracts

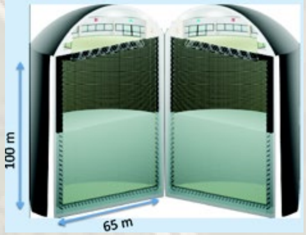
Possible ESSνSB schedule, ID #98

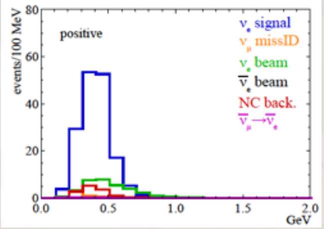
(2nd generation neutrino Super Beam)

ESS NEUTRINO SUPER BEAM

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

ESFRI





2012: inception of the project

2016-2019: beginning of COST Action EuroNuNet

2018: beginning of ESSνSB Design Study (EU-H2020)

2021: End of ESSνSB Design Study, CDR and preliminary costing

2022-2024: Preparatory Phase, TDR

2025-2026: Preconstruction Phase, International Agreement

2027-2034: Construction of the facility and detectors, including commissioning.

Muon option also possible.

2035-: Data taking

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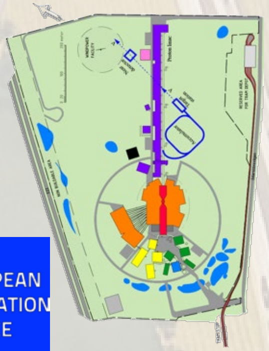
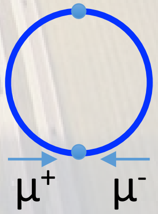
European Strategy Update



EUROPEAN SPALLATION SOURCE



Recommendation: After the CDR go to a Technical Design phase (TDR)