GT3 CONTRIBUTION

NEUTRINO PHYSICS

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(on behalf of GT3)

ESPPU IN2P3-IRFU Symposium meeting - 20th January 2025

DISCLAIMER

- This talk describes the content of the **2-page document** prepared by the **GT3** on neutrino physics.

  https://esppu.in2p3.fr/uploads/ESPPU2025-GT3-2pages-20250116150815.pdf

- It is a summary of a **10-page document** prepared within the **IRN Neutrino** framework which will also be submitted to ESPPU as stand alone document.

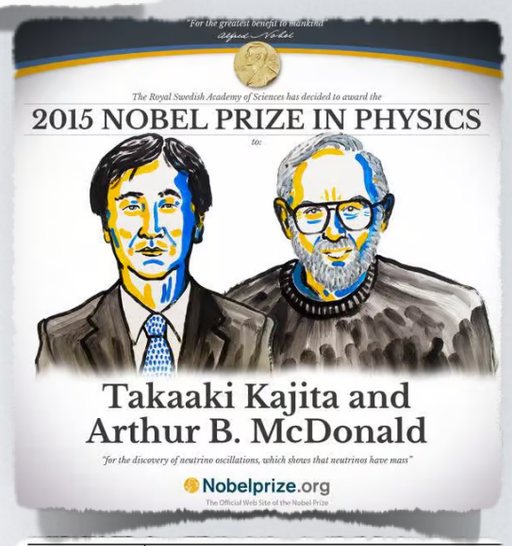
  https://esppu.in2p3.fr/uploads/ESPPU2025-IRNNeutrino-20241206150300.pdf

INTRODUCTION

Neutrino: one of the least known elementary particle

What we know

- **Neutrinos of 3 families have been detected and oscillations between the families was observed.**
- **The three mixing angles and the two mass splittings have been measured with precisions at the few percent level.**
- **Neutrino masses are the first and so far only manifestation of physics beyond the Standard Model in particle physics experiments.**



	Ref. [181] w/o SK-ATM	
NO	Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.03^{+0.12}_{-0.11}$	$2.70 \to 3.41$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.72^{+0.18}_{-0.23}$	$4.06 \to 6.20$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.203^{+0.056}_{-0.059}$	$2.029 \to 2.391$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$
$\delta_{\rm CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$	$2.437^{+0.028}_{-0.027}$	$2.354 \to 2.523$
IO	$\Delta\chi^2 = 2.3$	
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.03^{+0.12}_{-0.11}$	$2.70 \to 3.41$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.78^{+0.16}_{-0.21}$	$4.12 \to 6.23$
$\theta_{23}/^\circ$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.219^{+0.060}_{-0.057}$	$2.047 \to 2.396$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
$\delta_{\rm CP}/^\circ$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

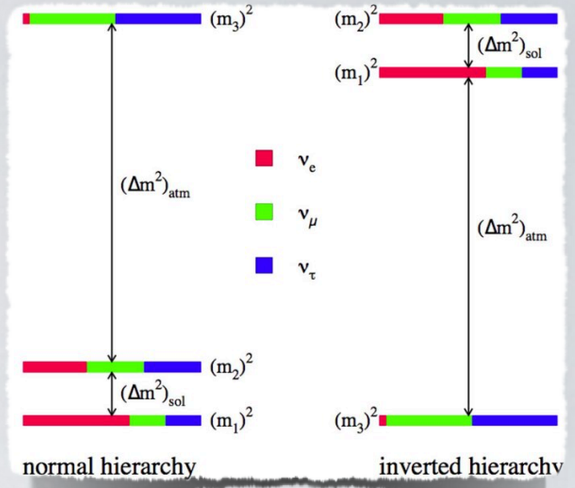
from PDG

INTRODUCTION

Neutrino: one of the least known elementary particle

What we do not know

- **The absolute value of their masses.**
- **Whether neutrinos are Dirac or Majorana fermions.**
- **The mass ordering (normal or inverted).**
- **Wether the charge-parity (CP) symmetry is violated in the lepton sector.**



The last two parameters will be measured in the next 10 years

- **Neutrino experiments aim at establishing the yet unknown fundamental properties of neutrinos and at unravelling their nature.**
- **The results of these experiments will be of great importance for particle physics, as well as for astrophysics and cosmology:**
  - ➡ *Possible assessment of Majorana nature of neutrinos, suggesting the existence of a new physics scale beyond the Standard Model.*
  - ➡ *Possible discovery of leptonic CP violation (a necessary ingredient of leptogenesis) in long baseline neutrino oscillations.*

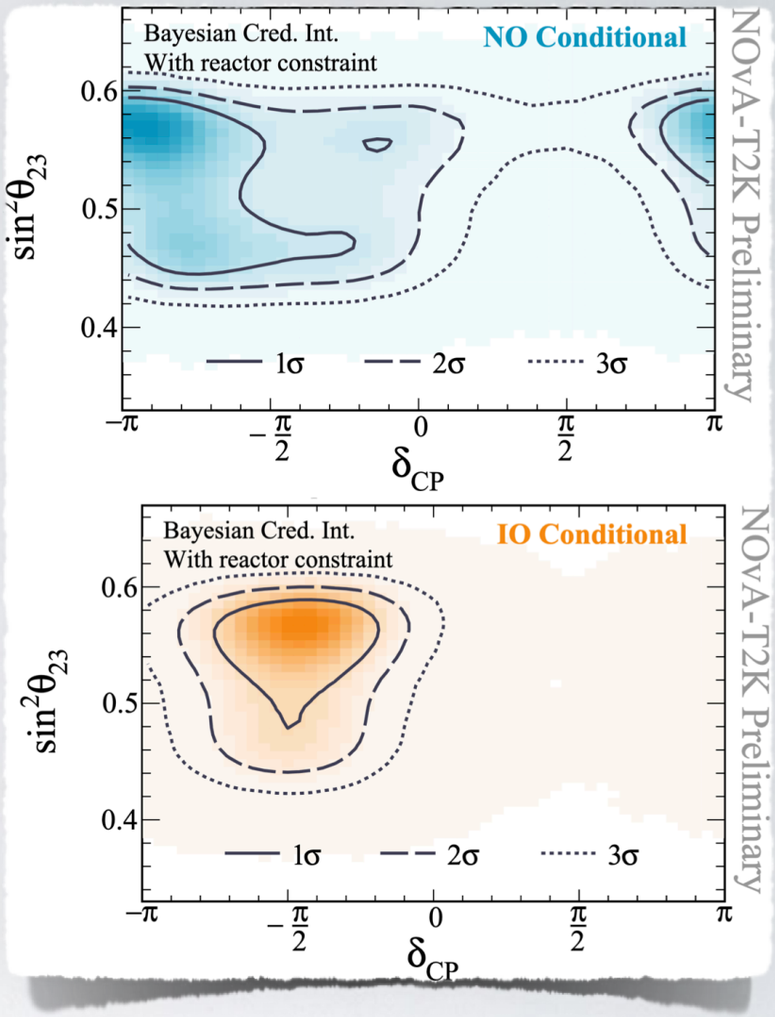
LONG BASELINE EXPERIMENTS

- The precise study of oscillations with Long Baselines (LBL) is a **privileged tool** to investigate standard and non-standard neutrino properties.

- The **main goals** of current and future LBL experiments are the **search for CPV** in the neutrino sector, the **determination of the neutrino mass ordering** (MO), and the **precise measurement** of the phase δ_{CP} and of the so called "atmospheric" parameters (θ_{23} and Δm^2_{32}).

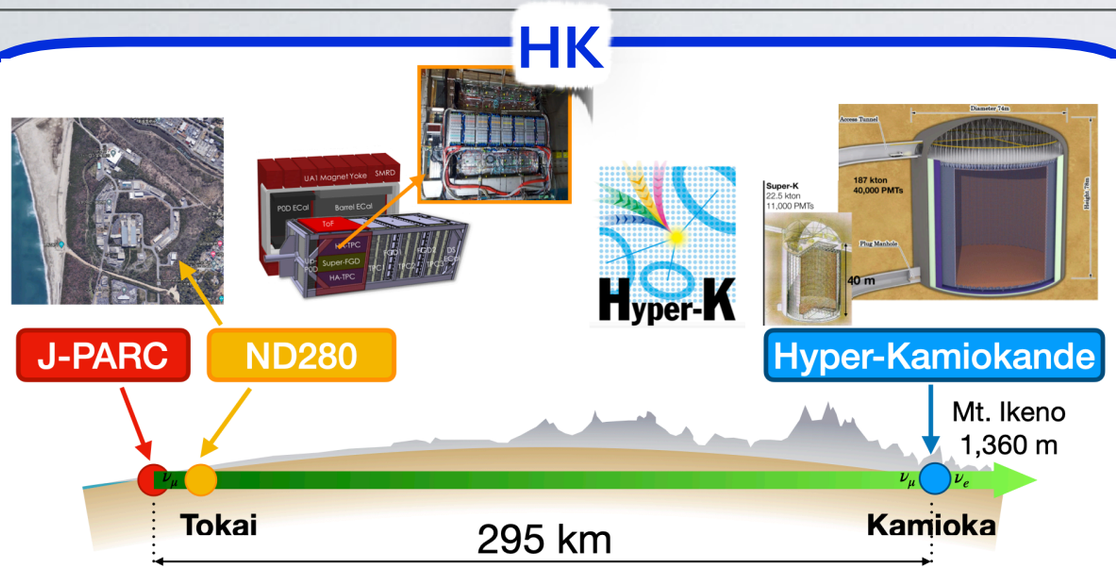
- T2K and NOVA are providing accurate measurements of neutrino oscillations and new tests of the standard PMNS oscillation paradigm, observed for the first time ν_e appearance in a ν_μ beam, and yielded first hints of CP-symmetry violation.

- The next generation experiments, Hyper-Kamiokande (HK) in Japan and the Deep Underground Neutrino Experiment (DUNE) in the US, represent the forefront of this endeavour.



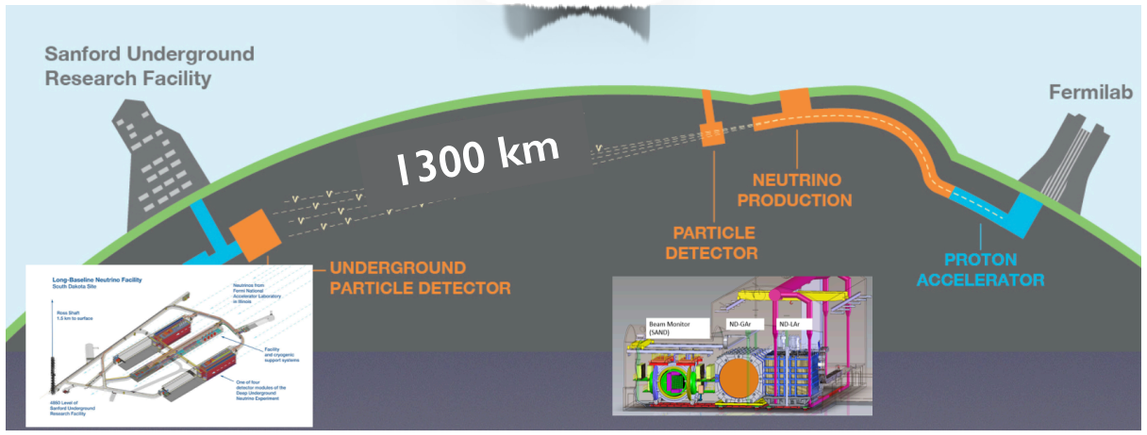
LONG BASELINE EXPERIMENTS

HK



- J-PARC 1.3 MW beam in JAPAN.
- Water Cherenkow technology (188 kton fiducial mass).
- Near detectors of T2K.

DUNE

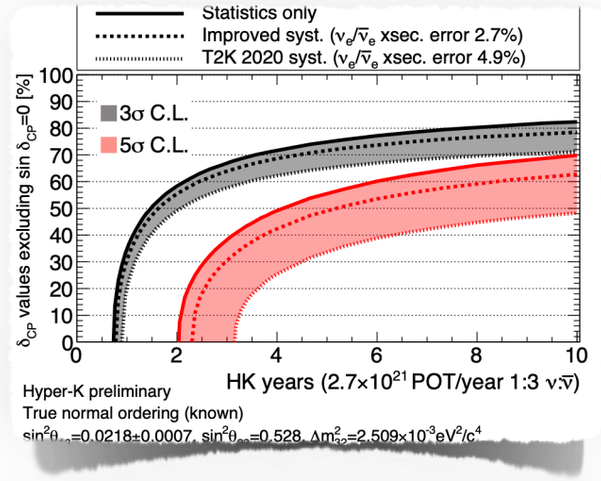


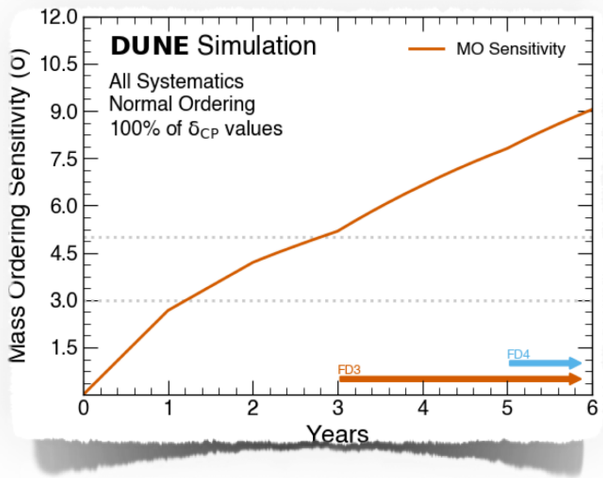
- Fermilab 2 MW beam in US.
- Liquid Argon TPC (40 kton fiducial mass).
- Near detector complex at Fermilab.

Complementary due to different baselines, energies, and detector technologies

The goals are:

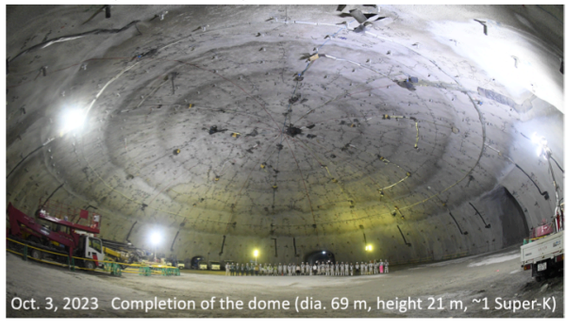
- ➡ Unprecedented sensitivity to CP-violation.
- ➡ Determination of the mass ordering.
- ➡ Precise measurement of oscillation parameters.

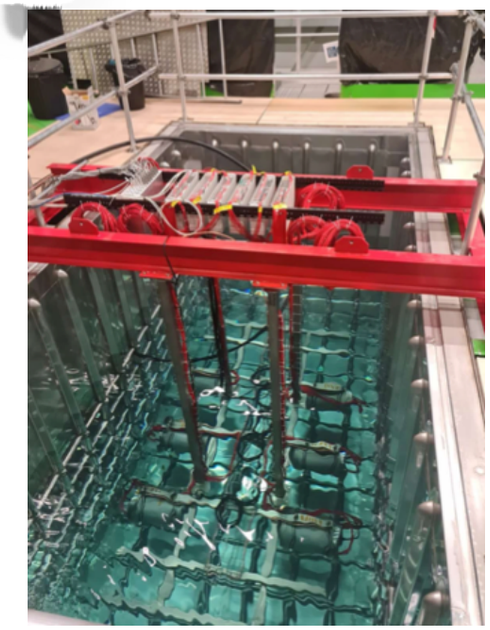




LONG BASELINE EXPERIMENTS

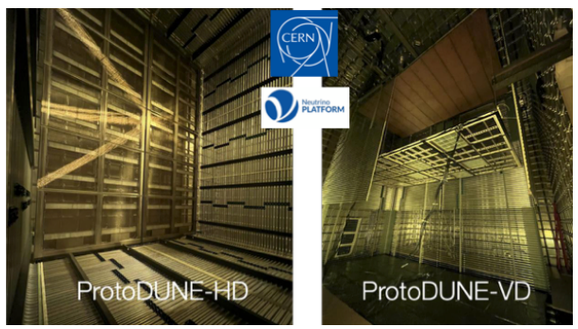
HK





- Excavation ongoing.
- PMT being produced.
- All electronic modules (1000) will be assembled and tested at CERN in 2025.
- France responsible for the time generation and distribution, and for the calibration of the readout electronics.
- France major player of the near detectors (TPCs and SFGD).
- Detector operation in 2027.

DUNE



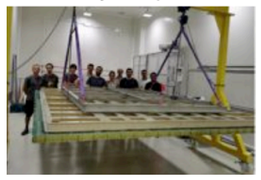
France – VD detector contributions

6 CNRS labs + IRFU
~80 people

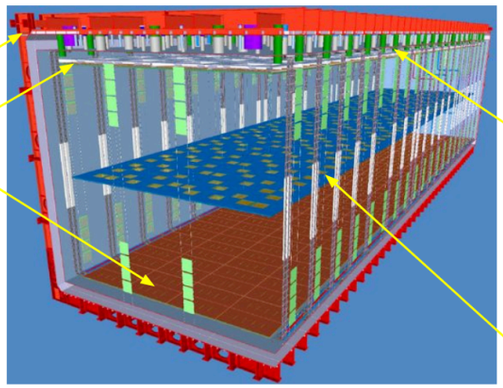
Signal feedthrough chimneys

CRP structures

Assembly of top CRPs

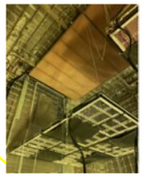


+ contribution to PIP-II



Funding from IN2P3/CNRS via IR*

Top drift charge readout electronics



Electronics for photon detection system
(Signal-over-fiber transmission and reception)

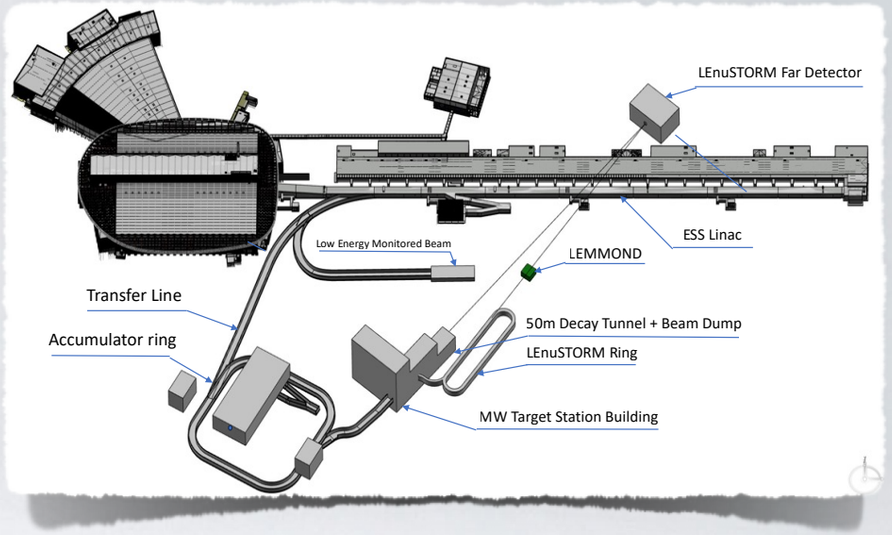
- Excavation completed.
- First Far Detector module (vertical drift) under construction.
- France leading the VD module construction: CRP, cold electronics and electronics for photodetection system.
- Test at CERN with ProtoDUNE since 2018 (data with ProtoDUNE-VD in 2025).
- Detector operation for physics with atmospheric neutrinos in 2029 (beam + ND in 2031).

LONG BASELINE EXPERIMENTS

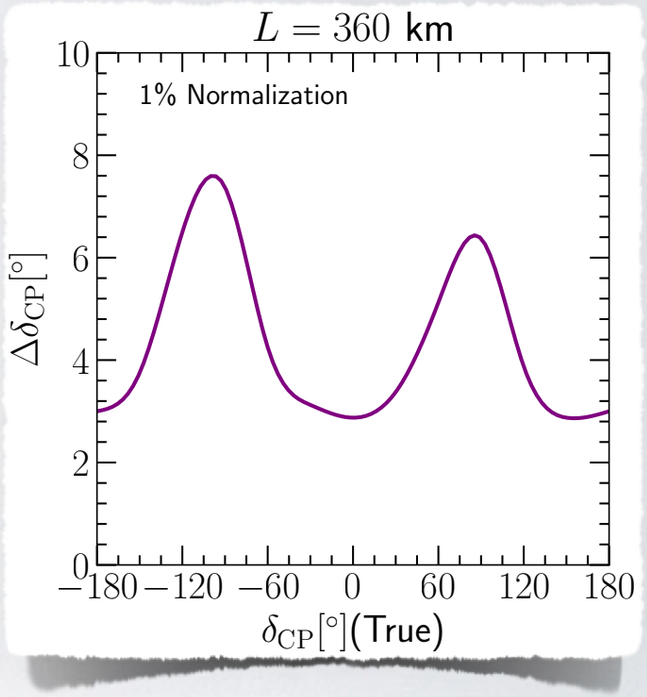
What's next?

- In the longer term, the ESSnuSB/ESSnuSB+ projects, funded by EU, investigate a unique possibility of creating a LBL experiment with unprecedented beam power in Europe, exploiting the neutron spallation source of 5 MW in Sweden.

- Such a study includes the design of a muon beam fostering R&D for future neutrino factories, and the possible development of a monitored/tagged neutrino beam.



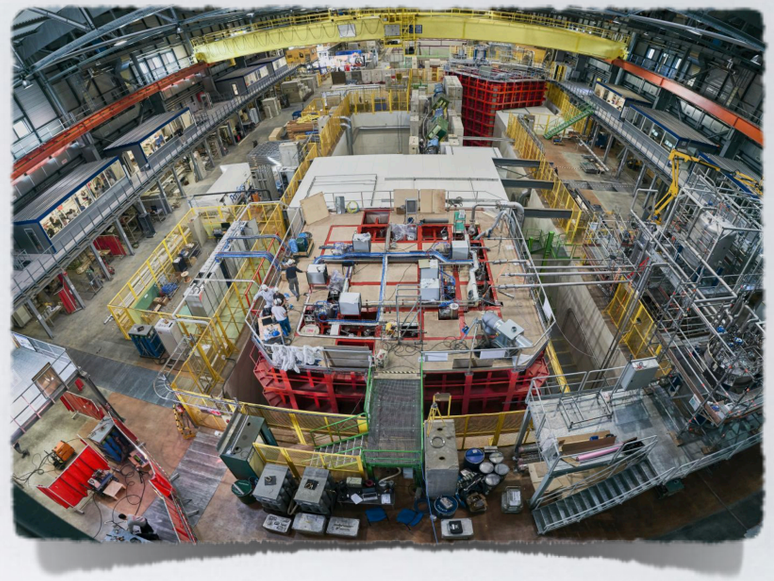
- **It is clear that with DUNE and HK conventional neutrino beams reached their limits. To go beyond something else is needed.**
- **Neutrino factories are an option ⇒ strong synergy with muon colliders.**



CERN NEUTRINO PLATFORM

- The CERN Neutrino Platform is a cornerstone of the European contribution to the worldwide neutrino physics program, supporting the design, testing, and validation of cutting-edge detectors for T2K, HK, and DUNE.

- **It provides invaluable infrastructure for detector assembly, cryogenic tests, and beam line, in a fully instrumented environment, easily accessible from Europe.**
- **It will be crucial for further detector developments envisaged for DUNE, with the module of opportunity, and for HK, with the second upgrade of the ND280 near detector.**
- **It is an absolutely crucial hub to enable proper coordination for detector developments, data analysis and phenomenological studies.**



Possible platform expansion

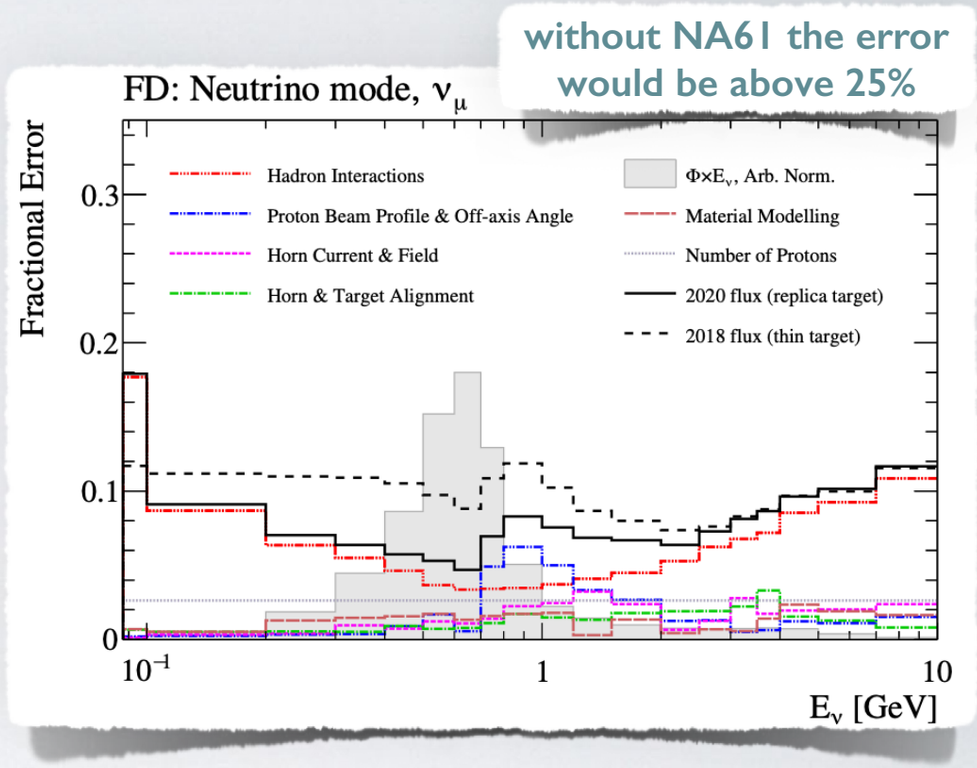
- **Support detector development for a variety of neutrino experiments beyond LBL (e.g. testing photo-detection technology also for neutrino telescopes, performing radio-purity studies for low energy solar neutrino measurements and $0\nu\beta\beta$)**

CERN ANCILLARY MEASUREMENTS

- **CERN plays a unique role for LBL** also outside the neutrino platform framework. The precision measurements of neutrino oscillations will ultimately be limited by complex systematic uncertainties due to nuclear physics effects in hadro-production in the beamline and in neutrino-nucleus interactions.

- **Ancillary measurements of hadro-production** (in NA61/SHINE) and of hadron and electron scattering on nuclei are of paramount importance to ensure the accuracy of neutrino oscillation measurements.

- **CERN already has all the facilities** to be a unique worldwide environment for such crucial measurement.



- Promoting **CERN as the worldwide platform** for such a supporting physics program is a compelling scenario to build a unique and distinct **role for the European physics community** in the neutrino oscillation domain (expecially considering that next generation experiments are in US and Japan).

A NEUTRINO BEAM AT CERN

- As suggested by the previous European Strategy, R&D have been carried out to support a new generation of neutrino cross section experiments at the GeV scale to boost the physics return of LBL projects.

  - **NP06/ENUBET:** *Neutrino Platform experiment at CERN aimed at designing a beam with sub-percent precision in the* ν_e *and* ν_μ *flux and O(10%) precision on the neutrino energy using* **Monitored Neutrino Beams.**

    ➡ Systematic uncertainties on the flux are removed by monitoring the rate of charged leptons in the decay tunnel and the ν_μ neutrino energy is inferred from the neutrino production angle. (i.e. the interaction vertex at the neutrino detector).

    ➡ This is equivalent to have a monochromatic ν_μ beam with a 10% width, whose **flux is known with <1% precision.**

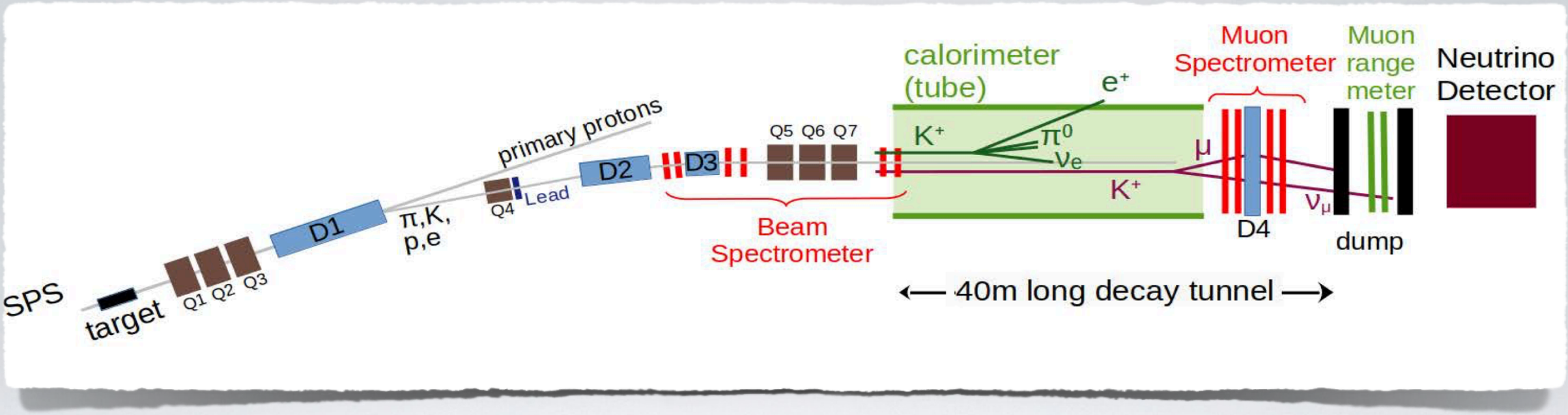
  - **NuTAG:** *Proposal to instrument the ENUBET beamline with fast silicon trackers.*

    ➡ The parent pion/kaons and the muons are tracked and the neutrino energy is reconstructed by kinematics.

    ➡ This is equivalent to have a monochromatic ν_μ beam with a 1% width and the **first tagged neutrino beam ever build.**

Under consideration at CERN in the framework of Physics Beyond Collider (SBN@PBC for Short Baseline Neutrinos at Physics Beyond Colliders)

A NEUTRINO BEAM AT CERN



- **SBN@PBC is a horn-less narrow-band beam originating from 400 GeV/c protons slowly extracted from the CERN SPS.**
- **The optimization ensures that the cross section measurements can be completed within a few years of data taking, without interfering with the rest of CERN's fixed-target program (e.g., SHIP).**
- **The proposal foresees to possibly using the ProtoDUNEs and WCTE (or its ≈100-ton extension) as neutrino detectors to perform cross section measurements using the same target as DUNE (liquid argon) and HyperKamiokande (water).**

CERN AS HUB FOR ANALYSIS AND THEORY

- **Theory** is a **crucial** part of the general effort of the neutrino community to understand the fundamental properties of neutrinos and to identify the new physics at the origin of their masses.

- It is therefore important to maintain a sustained activity in neutrino theory in order to be able to **fully exploit and interpret experimental results**, and to **guide experimental searches**.

- The advent of two major, complementary LBL neutrino experiments raises the challenge of **comparing and combining** their **results**. CERN can play a key role as a promoter and host of such joint efforts, leveraging the strong involvement of the European community in both experiments.

Key role of CERN which should be continued and increased

- **CERN serves as a vital hub for collaboration and exchange in neutrino physics, bringing together experimentalists and theorists from across Europe and beyond.**
- **CERN provides a powerful infrastructure for shared software platforms, Monte Carlo simulations, and computational resources, facilitating consistent data analysis across multiple experiments.**

CONCLUSIONS

- **Neutrino physics** has a **critical role** in the particle physics panorama.
- Many open questions still exists and **next generation of LBL experiments will surely provide measurements** to cast light on some of them.
- A **centralised European approach to neutrino physics at CERN**, relying on the **Neutrino Platform infrastructure**, is a **unique path** to ensure that the European physics community remains at the forefront of future scientific discoveries in the neutrino field.

Considering all that's been said… here is the most important take home message

The compelling physics case of neutrino experiments should be kept in mind in the overall vision of the future of European particle physics: the next collider project at CERN must be fundable in a way that is not detrimental, in terms of resources, to neutrino physics.

DISCUSSION

Focus and perimeter of ESPPU

- We are preparing the European Strategy Particle Physics Update

  - **Strategy** → focus on the physics outcome of 'big science' projects, which require large resources

  - **CERN** is organizing the EPPSU effort → focus on the projects at CERN

Therefore the main focus of the document is the LBL (T2K→HK, DUNE) and Neutrino Platform → we focused on the importance and the crucial role of Neutrino Platform also in the future

Also included ESSnSB as prospect for future LBL in Europe

- … but the European Neutrino Physics is more than that !

  We did include **big/strategic projects hosted in Europe and particularly supported by France**

  → ORCA+Km3Net (we also mentioned JUNO)

  → 0nbb at Gran Sasso with bolometers

  We included a sentence about the R&D for low energy detectors

  We included a sentence about proton decay and SuperNovae neutrinos at LBL far detectors

Two main messages (in bold in the document)

For neutrino physics at large

« The variety and importance of the neutrino program in Europe is a major asset for the community and is expected to play a major role for particle physics in the next decade.
This should be kept in mind in the overall vision of the future of European particle physics: the next collider project at CERN must be fundable in a way that is not detrimental, in terms of resources, to neutrino physics. »

For CERN role

« In summary, a centralised European approach to neutrino physics at CERN, relying on the Neutrino Platform infrastructure, is a unique path to ensure that the European physics community remains at the forefront of future scientific discoveries in the neutrino field »

By the way, we also shortly mentioned the possibility to extend the Neutrino Platform beyond LBL ...