Submission to European Strategy Preparatory Group

A realistic next-generation nucleon decay and neutrino experiment capable to probe leptonic CP violation

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I. INTRODUCTION

The recent results from Daya Bay [1], RENO [2] and Double Chooz [3] confirm that θ_{13} is, not only non-vanishing, but also sizable. Recent global fits [4, 5] give a best fit for θ_{13} between $\sin^2\theta_{13} = 0.024$ and 0.027 (with the larger values for an inverted hierarchy) and a 1σ error close to a 10%. This large value of θ_{13} opens the window to very fundamental measurements such as the CP-violating phase δ and the neutrino mass hierarchy. A measurement of δ can discriminate between models addressing the origin of the observed pattern of masses and mixings (the flavour puzzle) and could also imply the discovery of a completely new source of CP violation. The quark mixing matrix provides the only fundamental CP violation observed so far, which can be encoded in the reduced Jarlskog invariant $J = (2.96^{+0.20}_{-0.16})\cdot 10^{-5}$ [6]. However, this value has been shown to be too small to account for the observed baryon asymmetry of the Universe (BAU) [7]. The recent measurement of θ_{13} indicates that the corresponding quantity in the neutrino sector is $J \sim 0.29\sin\delta$, potentially four orders of magnitude larger. A measurement of δ could thus provide very illuminating information on the origin of the BAU. Regarding the neutrino mass hierarchy, its measurement not only also helps with the flavour puzzle, but it is also the key parameter to use as input in neutrinoless double beta decay searches exploring the Majorana nature of neutrinos. Neutrinos, being Standard Model singlets, are the only particles that potentially have a Majorana nature and could thus provide a new source of particle number violation, i.e. another key ingredient that could help us understand the origin of the BAU. We therefore regard these two measurements as fundamental, not only in neutrino physics, but in particle physics in general since they address questions as fundamental as the flavour puzzle and the origin of the matter excess that allows our very existence.

Ongoing and near future neutrino beams such as T2K [8] and Noνa [9] will provide the first $\sim 2\sigma$ hints for these two unknowns [10]. However, these experiments will remain statistically challenged even for the presently favoured large value of θ_{13} and new facilities will be needed to reach the 3 and, eventually, 5σ level. We believe that this value of θ_{13} allows these searches to be performed within a reasonable time interval by relatively modest upgrades of conventional neutrino beams to SuperBeam setups of 1 MW typical power, pointing to a next-generation neutrino far detector characterized by one order of magnitude larger active mass. Intermediate baselines of ~ 700 km offer good sensitivity to both observables if high statistics can be achieved [11, 12]. These baselines represent a compromise between matter effects strong enough so as to provide sensitivity to the mass hierarchy but not too strong so as to deplete the (anti)neutrino sample for (normal) inverted hierarchy and hinder the CP violation searches (that strongly benefit from having both beam polarities).

The current reference for the large mass far detector required is the 22.5 kt (50 kt) fiducial (total) water Čerenkov detector Super-Kamiokande (SK). Because of its mass, SK is also the world's most powerful scientific apparatus for neutrino physics and nucleon decay. In fact, the original physics program of Super-Kamiokande did not contemplate to be the far detector of a long baseline neutrino beam. SK has discovered atmospheric neutrino oscillations [13], has been vital to solve the solar neutrino problem [14], has measured precisely an important fraction of the elements of the leptonic mixing matrix (e.g. [15] and [16]), has observed, operating as K2K far detector, neutrino oscillations in a long baseline experiment for the first time and measured precisely its characteristics [17], and has given the first evidence, operating as T2K far detector, of the non-vanishing but value for θ_{13} [18]. Concerning proton-decay searches, SK currently provides the world's best limit [19, 20]. On the astrophysics side, SK (and its precursor Kamiokande) pioneered the field of neutrino astronomy, and is providing many of the world's best limits on various astrophysical objects such as Dark Matter (DM) and the Diffuse Supernova Neutrino Background, DSNB, also called relic supernova neutrinos [21, 22]. From the instrumentation point of view, the success of SK comes undoubtable from the water Čerenkov technique, which allows to instrument huge amounts of active mass with a relatively simple, reliable, understood and low cost technology.

Super-Kamiokande is operating already for 16 years. Even though it is still a truly valid scientific apparatus, its "small" fiducial mass makes it to be reaching the limit of interest for some of its main fundamental scientific objectives, proton decay being a paradigm. On the astrophysics side, the very strong R&D program [23] by SK on neutron tagging [24] will hopefully allow to SK the discovery, just-a-few-events though, of the DSNB. One order of magnitude larger fiducial mass would allow to extract very valuable information on fundamental questions like black hole formation and elementary particle interactions at very high densities.

Thus, we encounter ourselves in the time situation when a reasonable next generation of "very large size infrastructure" experiment has a fundamental scientific potential as it has never had any other major experimental project before.

In this proposal we sketch and justify the, in our opinion, most reasonable approach for that experiment within Europe.

II. THE OVERALL EXPERIMENT

A. The Beam

We will discuss the physics performance of a long baseline neutrino oscillation experiment based on a neutrino beam from the CERN accelerator complex pointing to a WC detector of 500 kt fiducial volume located at $\sim$ 700 km. We consider two possible cases for the neutrino beam. The first one features a neutrino energy peaking around $\sim$ 1.5 GeV, matching the first oscillation peak for the baseline considered. For its beam power we have taken 0.8 MW per year (assuming 10^7 useful seconds), which is likely to be within reach with modest upgrades of the current CNGS beam technology [25]. Extensive works in this direction have been carried out within the EU funded LAGUNA-LBNO program [26] and the approach would be very similar to that considered in the recently submitted EoI for a LBL experiment from CERN to the Pyhasalmi mine [27].

The second alternative corresponds to a lower energy beam, with a neutrino energy around $\sim$ 0.4 GeV but a higher intensity of 4 MW. This flux corresponds to the SuperBeam proposal studied within the "EUROnu" FP7 Design Study [28] and approximately matches the first oscillation peak at a baseline of 130 km: the distance between CERN and the Frejus underground laboratory [29–35]. In Ref. [11] it was shown that, for the presently favoured large values of θ_{13}, the physics reach of this flux, both for the discovery of CP violation and the mass hierarchy, significantly increased when observed closer to the second oscillation peak, and hence the longer $\sim$ 700 km baseline considered here. Both fluxes have been obtained from Ref. [36]. We have considered 5 years of data taken with each beam polarity.

B. The Large Mass, Far Detector

As of today, the two most reasonable sites within Europe for the location of a large WC far detector at $\sim$ 700 km distance from CERN are the "Laboratori Nazionali del Gran Sasso" (LNGS) and the "Laboratorio Subterráneo de Canfranc" (Canfranc Underground

Laboratory, LSC). With respect to the neutrino beam, the simplest approach is to upgrade the already available ν beam in Europe: the CERN's CNGS [25] pointing to the Grand Sasso Laboratory (LNGS), placing the far detector under the Grand Sasso mountain as a new experimental facility of the LNGS. However, there are several external factors that may exclude the LNSG option; the two most widely known are the difficulty to find a place for the necessary near detector and the foreseen extremely serious environmental and socio-political constraints that any project of expansion of the current LNGS will definitely encounter.

We therefore concentrate in the LSC as the location of the far detector. The CERN-Canfranc baseline is 650 km. The results for a baseline of 730 km, corresponding to the Gran Sasso option, are very similar and, in fact, slightly better for the sensitivity to the mass hierarchy, given the stronger matter effects. The LSC is one of the seven candidate sites to host a next-generation neutrino and proton-decay detector of the multi-kiloton type and was thoroughly studied within the EU-funded LAGUNA program [37]. Overall, it was concluded that a) the LSC was very well suited to place any of the considered LAGUNA experiments and, b) the Canfranc area is excellent to provide the social and living needs of the people forming a large Collaboration like LAGUNA [38].

We firmly believe that only with water Čerenkov technology one can realistically build and commission a successful, truly competitive, next-generation, 500 kt fiducial volume detector, for neutrino and nucleon decay physics within a reasonable time interval of less than 10 years. Another option contemplated by the community in Europe, with expected comparable physics performance, is a 100 kt liquid Argon (LArg) detector. Its instrumental and scientific interest is certainly maximum and it will probably represent the future of the field. However, we think that to be in the position to accomplish the needed technology and know-how, one or two successful intermediate steps (for instance 2 kt and 20 kt) are needed beforehand.

We therefore adopt the MEMPHYS option [39, 40]. A very detailed feasibility study for the LSC to host the MEMPHYS detector [41, 42] was carried out within the LAGUNA program [37]. All fundamental aspects were covered: geological, geotechnic, environmental, socio-economical etc. A pre-design of the three main caverns, auxiliary caverns, access tunnels for construction and running phases, all type of services, emergency routes end equipment, power, water, Rn-less air supplies etc. was made. For each of the main caverns a rather realistic elasto-plastic model calculation was performed to validate the pre-design

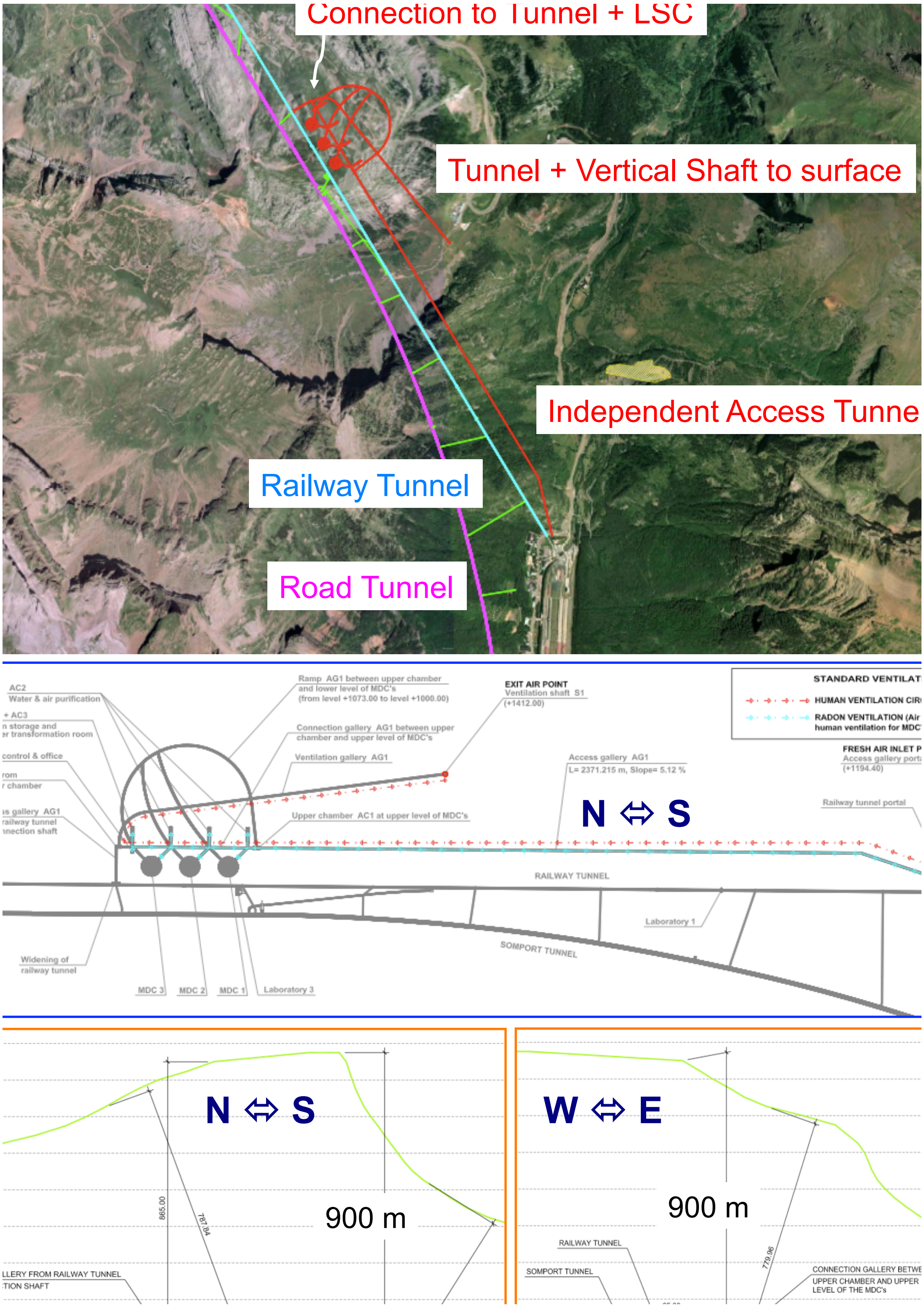

FIG. 1: General layout of the MEMPHYS detector at the LSC [http://www.lsc-canfranc.es/Docs/Experiments/LAGUNA/LSC_Revision_20100512.pdf]

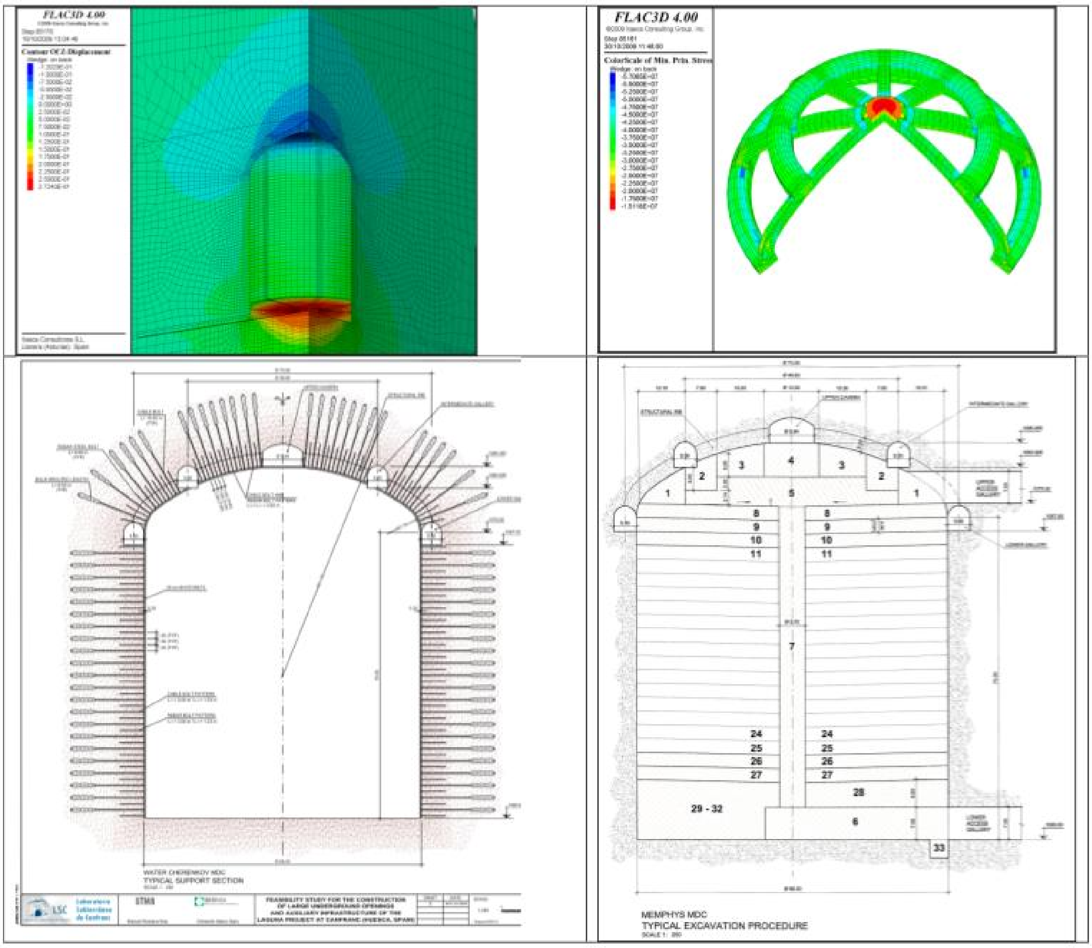

FIG. 2: Examples of calculations, pre-designs and excavation sequences for one MEMPHYS cavern at the LSC [http://www.lsc-canfranc.es/Docs/Experiments/LAGUNA/LSC_MEMPHYS_PLANS_Revision_20100512.pdf]

of the excavation and reinforcement of the main cavern. Also the full cost was estimated rather accurately: to have the facility built and operational including overheads (13%), industrial benefits (6%) etc. (but not, of course, the tanks and instrumentation) would cost 198.810.526,0 euros. Fig. 1 and Fig. 2 illustrate some aspects of this feasibility study.

III. PHYSICS REACH

A. Discovery and Measurement of Leptonic CP violation

The results obtained are summarized by Fig. 3, for details of the simulations see Refs. [11, 12]. Fig. 3-right shows the CP violation (CPV) discovery potential in terms of the χ^2 value

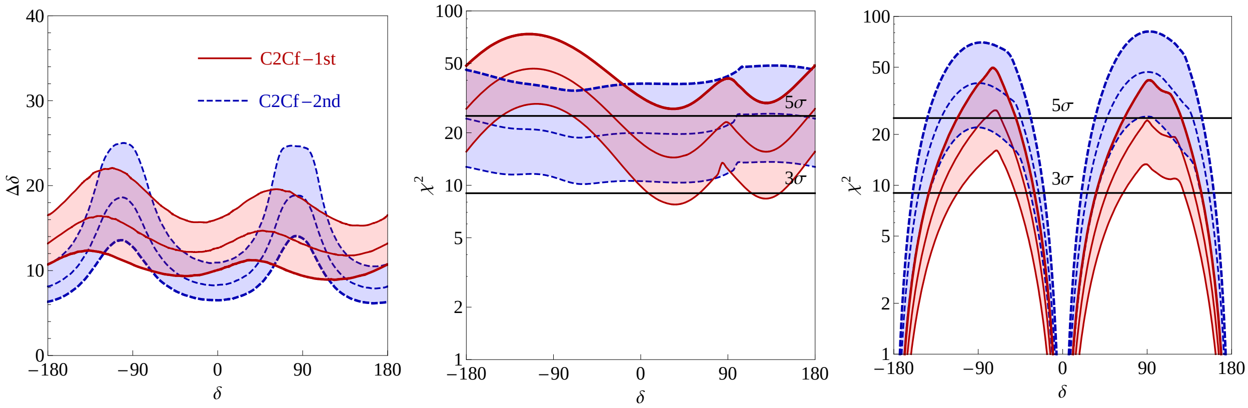

FIG. 3: Comparison of $\Delta\delta$ (left panel), the mass hierarchy (middle panel) and the CPV discovery potential (right panel) for the high energy beam of 0.8 MW close to the first oscillation peak (C2Cf-1st) and the lower energy 4 MW beam close to the second oscillation peak (C2Cf-2) observed at a 650 km baseline corresponding to the CERN to Canfranc distance. For all observables, the thicker lines the correspond to the maximum exposure considered (best results), while the other lines show the results after reducing the statistics by factors of 2 and 4.

with which each facility would be able to disfavour CP-conservation as a function of δ. A normal hierarchy (NH) is assumed (the results obtained assuming an inverted hierarchy, IH, are slightly better and do not alter significantly the main conclusions). The top lines (also thicker) correspond to the nominal setups, while the subsequent lines in each band are for reductions of the total exposure by factors of 2 and 4, to show how much a reduction of the beam power, detector mass or running time can be born without spoiling the physics performance of the facility. The CPV discovery potential for each scenario would therefore be the areas where the corresponding lines are above the corresponding value of the χ^2 for a given confidence level. As an example, the 3 and 5σ lines are shown.

For the nominal exposure, the 1.5 GeV and 0.8 MW setup at the first peak (C2Cf-1st) provides discovery potential to CP violation for a 63% (34%) of the possible values of δ at 3σ (5σ). These numbers lower to 51% (5%) for a factor 2 reduction in statistics and 35% (0%) for a factor 4. The lower energy and higher intensity option (C2Cf-2nd) would perform remarkably better, providing discovery potential for a 78% (62%) of the possible values of δ at 3σ (5σ) at nominal intensity. These numbers are reduced to 71% (49%) and 61% (4%) for reductions in statistics by factors of 2 and 4 respectively.

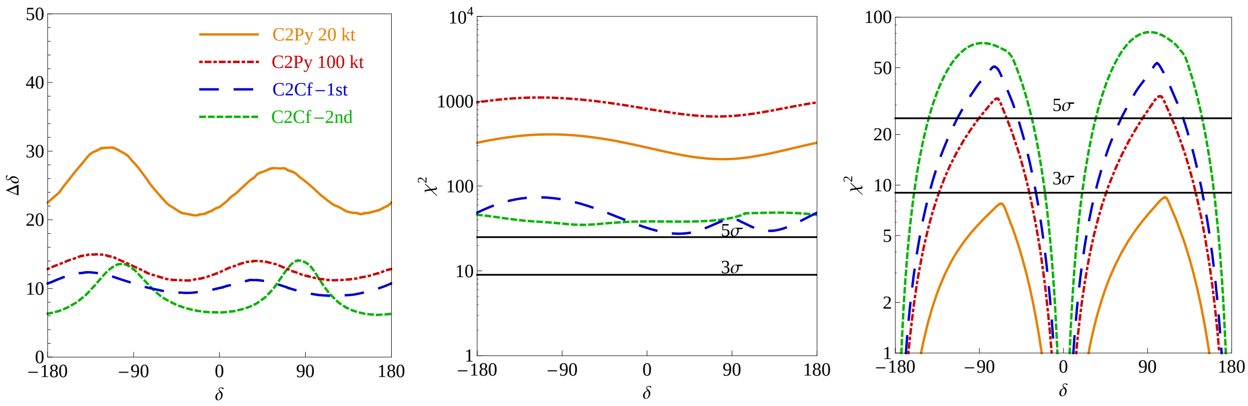

FIG. 4: Comparison of $\Delta\delta$ (left panel), the mass hierarchy (middle panel) and the CPV discovery potential (right panel) for the setups C2Py 20kt, C2Py 100 kt, C2Cf-1st and C2Cf-2nd.

Fig. 3 also shows the results for the achievable precision on δ (left) and the mass hierarchy discovery potential (middle). A normal hierarchy has been assumed in this case for both panels. In Fig. 3-left $\Delta\delta$ is defined as 1/2 of the 1σ allowed region in the measurement of the CP violating phase δ. As can be seen from the plots, both options would provide a similar sensitivity to δ overall. However, C2Cf-2nd has a significantly stronger dependence on δ with pronounced maxima around $\delta = \pm\pi/2$ (see Ref. [43] for a discussion) and deep minima close to CP-conserving values, which enhances its CP violation discovery potential with respect to C2Cf-1st.

The mass hierarchy discovery potential is depicted in the middle panel of Fig. 3. Here it is shown the χ^2 value with which each facility can disfavour the wrong mass hierarchy as a function of the true value of δ. The results for inverted hierarchy are very similar to these under the inversion $\delta \to -\delta$. As can be seen, for nominal statistics both alternatives provide a 5σ determination of the mass hierarchy for any value of δ. Reducing the statistics by a factor four the 3σ level can be reached for all δ for C2Cf-2nd and in almost all the parameter space for C2Cf-1st. These values would improve when combining with the large atmospheric neutrino sample that would be measured by the detector [34, 44]. Thus, this type of setup seems adequate to perform this measurement if no higher significance is required.

In Fig. 4 we compare the two versions of the CERN to Canfranc setup studied with "nominal" intensities to the recent proposal for a European long baseline neutrino oscillation experiment with a much longer baseline of 2300 km, the distance from CERN to the

Pyhasalmi mine, in Finland. This much longer baseline requires a correspondingly higher energy, peaked around 5 GeV to match the first oscillation peak. At these energies, deep inelastic scattering events start to dominate over quasielastic and the good particle identification and energy reconstruction properties of WC detectors significantly deteriorate. For this higher energy, a liquid argon (LAr) TPC has therefore been proposed instead. In a first phase, a 20 kton LAr detector would be located at the Pyhasalmi mine that could be later upgraded to 100 kton. We dub these two phases C2Py 20 kton and C2Py 100 kton in Fig. 4. Regarding the beam, the higher energy configuration of Ref. [36], peaked at around 5 GeV, and 0.8 MW was assumed. For the details of our simulation of this setup see Refs. [12, 43], based on Refs. [45–48]. We have considered 5 years of data taken with each beam polarity for both phases.

As can be seen in Fig. 4-center, this much longer baseline is mainly optimized for the measurement of the mass hierarchy. Indeed, even the first phase of C2Py with 20 ktons could provide a 10σ determination of the mass hierarchy for any value of δ. The large values of θ_{13} recently measured greatly enhance the matter effects leading to such an unambiguous determination. The drawback is that the very same matter effects greatly suppress the (anti)neutrino oscillations for (normal) inverted hierarchy. This in turn hinders the determination of δ and the exploration of CP violation, since these searches greatly benefit from comparing neutrino and antineutrino samples. Indeed, as shown by Fig. 4-left, the precision with which δ could be measured is better for the C2Cf-1st option than the C2Py 100 kton setup for any value of δ. The fraction of values for which CP violation, shown in Fig. 4-right, could be discovered is also significantly smaller for the C2Py 100 kton option: 54% (17%) for 3σ (5σ), to be compared with the 63% (34%) and 78% (62%) sensitivities that could be granted by the C2Cf-1st and C2Cf-2nd options respectively. Since some CP violating values of δ are arbitrarily close to CP conserving ones, sensitivity to CP violation for the whole parameter space can never be achieved. It is therefore desirable to maximize it, since this also provides measurements of δ with smaller error bars. Regarding the mass hierarchy discovery potential, on the other hand, once the desired confidence level has been reached a more accurate measurement is not particularly helpful, since it is a discrete parameter. For this reason, given that the large value of θ_{13} recently measured allows a 5σ determination of the mass hierarchy at moderate baselines, we believe this option to be more desirable since it optimizes the performance of the setup for the discovery of CP violation.

B. Other Neutrino Physics and Astrophysics and Nucleon Decay

As discussed in the introduction, to advance in our knowledge of fundamental properties of Nature on neutrino physics, astrophysics and nucleon-decay, a 500 kt fiducial water Čerenkov detector, such as MEMPHYS, represents the necessary next-generation experiment. We summarize here the estimations done for similar setups [39, 45, 49, 50], for the most important of the expected physics achievements.

Atmospheric Neutrinos. High statistics atmospheric neutrino data in this type of detectors provide a complementary probe of neutrino oscillations to the beam searches. Particularly due to the large value of θ_{13}: the expected significance for the mass hierarchy determination is more than 3σ provided $\sin^2\theta_{23} > 0.4$. It is expected to be able to discriminate between $\sin^2\theta_{23} < 0.5$ (first octant) and > 0.5 (second octant) if $\sin^2(2\theta_{23})$ is less than 0.99.

Solar Neutrinos. The day/night asymmetry of the solar neutrino flux, concrete evidence of the matter effect on oscillations, could be discovered and then precisely measured by the detector, given that the detector up-down response can be understood to better than about 1%. The detector can provide short time and high precision variability analyses of the solar core activity. The solar core temperature can be monitored within a few percent accuracy day by day, and to a tenth of a percent over the period of several months.

Neutrino Astrophysics. Very high statistical observations of supernova neutrinos are expected for galactic supernovae, for instance $\sim 200,000$ events if at 10 kpc. Thus, with this detector we can measure detailed time profile and temperature variation during the burst: the neutronization phase, the initial burst phase which emit ν_e's etc. The direction to the supernova can be determined with an accuracy of about 2 degrees using ν_e-scattering events (10 kpc). Moreover, by studying supernova neutrinos, currently unknown properties of neutrinos can be investigated too. A paradigm is the mass hierarchy: the ratio of the average energy of time-integrated neutrino spectra, $\tau_E =< E_{\bar{\nu}_\mu} > / < E_{\bar{\nu}_e} >$, could be measured with a precision at the level of few percent such that, given the large value of θ_{13}, it would make possible to distinguish normal from inverted mass hierarchy.

Supernova relic neutrinos provide information on fundamental questions like elementary particle interactions at very high densities, black hole formation and the history of massive stars in the universe. For instance, the measurable spectrum of DSBN is the red-shifted sum of the contribution of supernova neutrinos from every epoch of the universe. It is crucial to reach the lowest possible detectable energy because the contribution from early epoch supernovae is expecting to be distributed at lower energy. This could be achieved by dissolving 0.1% gadolinium in the water, then the neutron coincidence signal from the 8 MeV gamma cascade will remove largely spallation and neutrino atmospheric backgrounds, making them manageable for the measurement. This way we expect ~ 800 DSBN events in the range $10-30$ MeV in 10 years of running assuming 67% efficiency for tagging neutrons.

Dark Matter. Large neutrino detectors could also shed light on the nature of another of the present fundamental unknowns in astroparticle physics: the nature of Dark Matter. Indeed, they can potentially detect indirectly Dark Matter from its decay products and could even provide information to their relative couplings to different Standard Model particles through its different branching ratios by exploiting the different energy spectra of the final state neutrinos [51].

Nucleon Decay. We concentrate in the two modes that are the subject of most intense interest within the community $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$. If the proton lifetime is shorter than $\sim 6\times10^{34}$ years for the $p \to e^+\pi^0$ mode, or shorter than $\sim 1\times10^{34}$ years for $p \to \bar{\nu}K^+$, signals over the atmospheric neutrino background events with a 3σ significance can be collected in the first 10 years of running.

Despite of the rather stringent results by Super-Kamiokande, the nucleon decay results from this detector will overtake Super-Kamiokande in less than one year. Already within 10 years of running the detector can cover most of the predicted ranges of the major GUTs models. After 20 years, the 90% CL limit for the $p \to e^+\pi^0$ lifetime will reach $\sim 2 \times 10^{35}$ years and $\sim 3 \times 10^{34}$ years for the $p \to \bar{\nu}K^+$ lifetime.

IV. SUMMARY

We have shown that the proposed neutrino oscillation experiment at an intermediate baseline of ~ 700 km can simultaneously address with high significance these measurement of δ and the neutrino mass hierarchy, two fundamental parameters for our understanding of flavour physics and the origin of the BAU. This baseline, closely matching the CERN to Canfranc distance, represents an optimal compromise between matter effects strong enough so as to provide sensitivity to the mass hierarchy but not too strong so as to deplete the (anti)neutrino sample for (normal) inverted hierarchy and hinder the CP violation searches. Large statistics is however needed to reach the desired confidence level and thus a very large far detector needs to be exploited. We have shown that the well-tested Water Čerenkov technology provides an ideal solution with the possibility of a very large ($\sim$ 500 kton fiducial) detector to provide the necessary statistics. Such a detector comes with an extremely rich physics programme of its own. Beyond its astrophysical interest as a neutrino telescope, such a large detector could greatly improve over the present bounds on proton decay, thus probing Grand Unification Theories and scales, something impossible at colliders. It could also shed light on the nature of another of the present fundamental unknowns in astroparticle physics: the nature of Dark Matter.

To summarize, we believe that a large $\sim$ 500 kton fiducial water Čerenkov detector coupled with an intense neutrino beam from CERN at a baseline of $\sim$ 700 km, represents an invaluable probe to fundamental questions such as the origin of the BAU asymmetry, the flavour puzzle, Grand Unification and the nature of Dark Matter.

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[1] F. An et al. (DAYA-BAY Collaboration), Phys.Rev.Lett. **108**, 171803 (2012), 1203.1669.

[2] J. Ahn et al. (RENO collaboration), Phys.Rev.Lett. **108**, 191802 (2012), 1204.0626.

[3] Y. Abe et al. (DOUBLE-CHOOZ Collaboration), Phys.Rev.Lett. **108**, 131801 (2012), 1112.6353.

[4] M. Tortola, J. Valle, and D. Vanegas (2012), 1205.4018.

[5] G. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, et al. (2012), 1205.5254.

[6] J. Beringer et al. (Particle Data Group), Phys. Rev. **D86**, 010001 (2012).

[7] M. Gavela, P. Hernandez, J. Orloff, and O. Pene, Mod.Phys.Lett. **A9**, 795 (1994), hep-ph/9312215.

[8] Y. Itow et al. (T2K Collaboration), pp. 239–248 (2001), hep-ex/0106019.

[9] D. Ayres et al. (NOvA Collaboration) (2004), hep-ex/0503053.

[10] P. Huber, M. Lindner, T. Schwetz, and W. Winter, JHEP **0911**, 044 (2009), 0907.1896.

[11] P. Coloma and E. Fernandez-Martinez (2011), 1110.4583.

[12] P. Coloma, E. Fernandez-Martinez, and L. Labarga (2012), 1206.0475.

[13] Y. Fukuda et al. (Super-Kamiokande Collaboration), Phys.Rev.Lett. **81**, 1562 (1998), hep-

ex/9807003.

[14] S. Fukuda et al. (Super-Kamiokande Collaboration), Phys.Rev.Lett. **86**, 5656 (2001), hep-ex/0103033.

[15] Y. Ashie et al. (Super-Kamiokande Collaboration), Phys.Rev. **D71**, 112005 (2005), hep-ex/0501064.

[16] J. Hosaka et al. (Super-Kamiokande Collaboration), Phys.Rev. **D73**, 112001 (2006), hep-ex/0508053.

[17] M. Ahn et al. (K2K Collaboration), Phys.Rev. **D74**, 072003 (2006), hep-ex/0606032.

[18] K. Abe et al. (T2K Collaboration), Phys.Rev.Lett. **107**, 041801 (2011), 1106.2822.

[19] K. Kobayashi et al. (Super-Kamiokande Collaboration), Phys.Rev. **D72**, 052007 (2005), hep-ex/0502026.

[20] H. Nishino et al. (Super-Kamiokande Collaboration), Phys.Rev.Lett. **102**, 141801 (2009), 0903.0676.

[21] M. Malek et al. (Super-Kamiokande Collaboration), Phys.Rev.Lett. **90**, 061101 (2003), hep-ex/0209028.

[22] K. Bays et al. (Super-Kamiokande Collaboration), Phys.Rev. **D85**, 052007 (2012), 1111.5031.

[23] T. Yano (Super-Kamiokande) (2012), talk at the ICHEP 2012Conference, Melbourne, URL `http://indico.cern.ch/contributionDisplay.py?contribId=374&confId=181298`.

[24] F. Beacom and M. Vagins, Phys.Rev.Lett. **93**, 171101 (2004).

[25] CNGS (project), URL `http://proj-cngs.web.cern.ch/proj-cngs`.

[26] The LAGUNA-LBNO Consortium (2011), e.U. Grant Agreement No. 284518 FP7-INFRA-2011-1.

[27] A. Stahl et al. (2012), expression of Interest, SPSC-EOI-007.

[28] EUROnu (2008), e.U. Grant Agreement No. 212372 FP7-INFRA-2007-1.

[29] J. J. Gomez-Cadenas et al. (CERN working group on Super Beams), pp. 463–481 (2001), hep-ph/0105297.

[30] A. Donini, E. Fernandez-Martinez, P. Migliozzi, S. Rigolin, and L. Scotto Lavina, Nucl.Phys. **B710**, 402 (2005), hep-ph/0406132.

[31] J. E. Campagne and A. Cazes, Eur.Phys.J. **C45**, 643 (2006), hep-ex/0411062.

[32] A. Donini, E. Fernandez-Martinez, and S. Rigolin, Phys.Lett. **B621**, 276 (2005), hep-ph/0411402.

[33] A. Donini, E. Fernandez-Martinez, D. Meloni, and S. Rigolin, Nucl.Phys. **B743**, 41 (2006), hep-ph/0512038.

[34] J.-E. Campagne, M. Maltoni, M. Mezzetto, and T. Schwetz, JHEP **0704**, 003 (2007), hep-ph/0603172.

[35] A. Longhin, Eur.Phys.J. **C71**, 1745 (2011), 1106.1096.

[36] A. Longhin (2010), URL `http://irfu.cea.fr/en/Phocea/Pisp/index.php?id=72`.

[37] The LAGUNA Consortium (2008), e.U. Grant Agreement No. 212343 FP7-INFRA-2007-1.

[38] L. Labarga (LAGUNA Consortium), Acta Phys. Polon. **B41**, 1765 (2010).

[39] A. de Bellefon, J. Bouchez, J. Busto, J.-E. Campagne, C. Cavata, et al. (2006), hep-ex/0607026.

[40] L. Agostino et al. (MEMPHYS project) (2012), 1206.6665.

[41] The LAGUNA Consortium (Feasibility Study), URL `http://http://www.lsc-canfranc.es/Docs/Experiments/LAGUNA/LSC_Revision_20100512.pdf)`.

[42] The LAGUNA Consortium (Feasibility Study), URL `http://http://www.lsc-canfranc.es/Docs/Experiments/LAGUNA/LSC_MEMPHYS_PLANS_Revision_20100512.pdf)`.

[43] P. Coloma, A. Donini, E. Fernandez-Martinez, and P. Hernandez (2012), 1203.5651.

[44] P. Huber, M. Maltoni, and T. Schwetz, Phys.Rev. **D71**, 053006 (2005), hep-ph/0501037.

[45] T. Akiri et al. (LBNE Collaboration) (2011), 1110.6249.

[46] S. K. Agarwalla, T. Li, and A. Rubbia (2011), 1109.6526.

[47] P. Coloma, T. Li, and S. Pascoli (2011), 1110.1402.

[48] P. Coloma, T. Li, and S. Pascoli (2012), 1206.4038.

[49] D. Autiero, J. Aysto, A. Badertscher, L. B. Bezrukov, J. Bouchez, et al., JCAP **0711**, 011 (2007), 0705.0116.

[50] K. Abe, T. Abe, H. Aihara, Y. Fukuda, Y. Hayato, et al. (2011), 1109.3262.

[51] O. Mena, S. Palomares-Ruiz, and S. Pascoli, Phys.Lett. **B664**, 92 (2008), 0706.3909.