High Precision Neutrino Unitarity Possible?

CNRS/IN2P3 2020 Prospect on Neutrino Physics

T. J. C. Bezerra[5], M. Bongrand[3], A. Cabrera*[3,4], E. Chauveau[1], M. Grassi[3], P. Loaiza[3], L. Manzanillas[3], C. Marquet[1], M. Obolensky[0], M. S. Pravikoff[1], L. Simard[3], B. Viaud[5], C. Volpe[0], and F. Yermia[5]

[0]APC, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité University, 75205 Paris Cedex 13, France
[1]CENBG, UMR5797, Université de Bordeaux, CNRS/IN2P3, F-33170, Gradignan, France
[2]CPPM, Aix Marseille University, CNRS/IN2P3, Marseille, France
[3]LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
[4]LNCA Underground Laboratory, CNRS/IN2P3 - CEA, Chooz, France
[5]SUBATECH, CNRS/IN2P3, Université de Nantes, IMT-Atlantique, 44307 Nantes, France

September 20, 2019

The exploration of the *Standard Model* (SM) leptonic mixing has been led by the study of the *neutrino* (ν) *oscillations* phenomenon, whose discovery was acknowledged by the 2015 Nobel prize in physics. Half a century of experimental and theoretical effort has established and demonstrated consistency with the $3\,\nu$ model, implied by its three family solution. While no direct significant manifestation for physics beyond the Standard Model (BSM) has been found, the SM is known not to suffice to explain fully today's observed phenomenology. In the forthcoming decade (2020-2030), most oscillation parameters are expected to yield sub-percent precision. Such a knowledge opens the possibility to experimentally test for BSM manifestation(s) via the direct exploration of the PMNS matrix unitarity for the first time. Any significant deviation might, in turn, evidence the existence of non-standard states (i.e. new neutrino) and/or interactions, thus allowing for direct discovery potential. Even if no deviation was found, the PMNS matrix structure, very different from its CKM counterpart, is of fundamental important to our understanding of the flavour sector beyond the SM. In this document, we shall briefly review today's PMNS unitarity status in the context of existing and future particle physics programme within the next decade. As outcome, we identify the possible need for a missing experiment, here called Super Chooz, to address directly the compelling unitarity test with unique impact in the field. Such a program will additionally and coherently reinforce the physics of all planned experiments, indirectly improving both the CP violation and mass ordering forthcoming measurements. The potential surrounding Super Chooz embodies a unique opportunity, due to several described circumstances, likely to boost the CNRS/IN2P3 leadership and excellence in the field.

Today's neutrino oscillation experimental evidence is consistent with a $3\,\nu$ framework [1]. This is in agreement with the observed three families of charged fermions making part of the *Standard Model* (**SM**). While few inconclusive indications for possible discrepancy have been reported, intense exploration has cornered the remaining solution phase-space to marginal region(s) [2] – still not fully ruled out. Such discrepancies remain either or both non-significant and appear associated to experimental issues not unambiguously consistent with robust manifestations of physics beyond the Standard Model (**BSM**). Understanding them remains important.

Since ν oscillation is the macroscopic manifestation of the quantum interference of neutrino mass states during their propagation and the mixing among mass (ν_1, ν_2, ν_3) and weak-flavour (ν_e, ν_μ, ν_τ) eigenstates, the entire phenomenon is characterised in terms of two *mass squared difference* (δm^2 and Δm^2)[1] and three *mixing angles* (θ_{13}, θ_{12}, θ_{23}), embedded in the 3×3 **PMNS** matrix, which is the **CKM** quark counterpart. This simplified parametrisation implies a critical assumption: the PMNS matrix is *unitary*; hence labelled U. This same condition allows for a complex phase leading to CP violation[2] during mixing. There is no a priori prediction for any such parameters (6), so each must be measured to allow the phenomenological $3\,\nu$ model characterisation of today's observations as well as possible searches for significant deviations between data and model, where discoveries may lay. It is worth noticing that the unitarity is an assumption that must be explicitly tested when considering hypothetical BSM physics. However, testing the non-unitarity implies addressing a much larger system of equations since the θ_{13}, θ_{12}, θ_{23} parametrisation no longer stands, by definition.

For about 50 years, the experimental community has been devoted to the measurement of each of the neutrino oscillation parameters. The key realisation was that behind the historically called *solar* and *atmospheric anomalies*, there is one single phenomenon: *neutrino oscillation*. However, the 2015 Nobel prize [3] discovery acknowledgement awaited the observation of the predicted new oscillation, driven by θ_{13}. This was only significantly observed in 2011-2012 by Double Chooz (**DC**) [4], Daya Bay (**DYB**) [5] and **RENO** [6] experiments. Now we know neutrinos are massive even though we have not been able to measure its mass directly [7]. Today's knowledge can be effectively characterised by the precision of each parameters, since no significant deviations have been found, as summarised in Table 1. While θ_{12} and θ_{23} are large, θ_{13} is very small. As of mid-2019, all parameters are known

*CNRS/IN2P3 Contact: anatael@in2p3.fr and +33 675 388 007.

[1]In the literature, δm^2 and Δm^2 provide brief notation for the so called "solar" (Δm^2_{12}) and "atmospheric" (Δm^2_{23} or Δm^2_{13}) cases, respectively.
[2]Any CP violating phenomenon implies different manifestation for matter and anti-matter. This was discovered in the 60's with quarks (CKM).

	current knowledge up to 2020			predicted knowledge around 2030		
	precision (%)	dominant	global (%)	precision (%)	dominant	technique
θ_{12}	3.0	SNO	2.3	$\leq$1.0	JUNO	*reactor*
θ_{23}	5.0	NOvA	2.0	$\sim$1.0	DUNE+HK	*beam*
θ_{13}	1.8	DYB	1.5	1.5	DC+DYB+RENO	*reactor*
δm^2	2.5	KL	2.3	$\leq$1.0	JUNO	*reactor*
$\|\Delta m^2\|$	3.0	DYB+T2K	1.3	$\leq$1.0	JUNO+DUNE+HK	*reactor+beam*
sign(Δm^2)	unknown	SK	@ 3σ	measure	JUNO+DUNE+HK	*reactor+beam*
$\delta_{\rm CP}$	unknown	T2K	@ 2σ	measure	DUNE+HK	*beam*

Table 1: **Neutrino Oscillation Knowledge.** As of July 2019, current and predicted knowledge on $3\,\nu$ oscillation model is summarised in terms of the precision per parameter. The different columns show today's single experiment precision, dominant experiment, today's global precision (NuFit 4.0), predicted precision and best experiment along with the dominant technique used. The entire neutrino oscillation sector will be characterised using reactors and beams. This is not surprising since such man-made ν's are best controlled in terms of baseline and systematics, as compared to atmospheric and solar ν's. θ_{12} and θ_{23} will be largely improved by JUNO and DUNE+HK, respectively. JUNO will pioneer the sub-percent precision in the field. Interestingly, there is no foreseen capability to improve today's DC+DYB+RENO precision on θ_{13}, whose knowledge will go from today's best to future worst, unless a dedicated experiment is proposed. δm^2 will be dominated by JUNO while Δm^2 will be constraints by both JUNO and DUNE+HK. The unknown mass ordering will be addressed mainly JUNO and DUNE using vacuum oscillations and matter effects, respectively. Global data analysis suggests a possible favoured normal ordering solution at $\sim 3\sigma$'s, dominated Super-Kamiokande [8] (SK) data. Any deviation between JUNO and DUNE would be of great interest. The unknown $\delta_{\rm CP}$ depends on DUNE+HK. Global data, dominated by T2K [9], disfavours CP conservation (0 or π solutions) at $\sim 2\sigma$'s. Despite a key role in the field, the atmospheric neutrino experiments such as IceCube [10] and ORCA [11] are not expected to lead the ultimate precision by 2030, but intermediate results around 2025, if possible.

to the few percent (<2.5%) upon combining all experiments data. Two major unknowns remain: *atmospheric mass ordering*[3] and the *CP violation phase*. There is preliminary evidence [1] amounting suggesting a) normal mass ordering is favoured at $\sim 3\sigma$'s and b) CP-conservation is disfavoured at $\sim 2\sigma$'s. The former suggests no bounds in the phase-space to be explored by future $\beta\beta$ searches experiments. Despite major success, this precision is still considered limited to address the PMNS unitarity that might manifest. Although unknown, the interest is expected to raise upon $\leq$1% precision.

In the first half of 2020 decade, the sub-percent precision regime is expected. This will start with measurements of θ_{12} and $\delta m^2$by **JUNO** [12], based in China. **DUNE** [13] and **HK** [14], based in USA and Japan, respectively, are expected to provide the ultimate knowledge on θ_{23} during the second half of the decade. The knowledge of Δm^2, including the mass ordering resolution, is expected to be led by both JUNO and DUNE using complementary vacuum and matter effects approaches, respectively. Surprisingly, no experiment is able to significantly improve today's θ_{13} precision (1.5%), while all experiments depend strategically on it for both CP-violation and mass ordering. Our θ_{13} knowledge remains dominated by 2010's reactor data. By 2030, only experiments relying on artificially produced neutrinos, reactors and beams, will dominate the ultimate neutrino oscillation knowledge, as shown in Table 1. Thus, beyond 2020, the field is expected to be shaped by a few large (or huge) experiments with the highest budgets and largest (>500 scientists) collaboration per experiment in the history of neutrino research. The CNRS/IN2P3 has participation to all, JUNO, DUNE and HK experiments, even if HK remains to be approved. Hence, no major neutrino oscillation experiment is envisaged in Europe for a decade.

In summary, upon the decade 2020-2030, the field will be reaching an overall sub-percent precision in all terms except for θ_{13}. The unknown mass ordering and CP violation are expected to be measured within 2030 with today's data already allowing some hinted solutions at a few σ level. Hence, we will have all (6) parameters known by 2030. Some may wonder *have we reached the practical end of this research line?* Arguably, it is difficult to go larger than JUNO+DUNE+HK experiments, implying a world scale effort similar to the LHC program. We must therefore exhaustively ensure that we have all needed for the most pertinent phase-space to be explored in the next decade. In order words, we must ensure to be able to squeeze the most from those billions-worth of data by 2030. Addressing this includes, most importantly, considering the foreseeable field landscape upon the results by all the forthcoming experiments. Otherwise said, we must ensure that we are not missing anything compromising our ability to challenge the SM, thus maximising our deepest sensitivity to any BSM possible manifestation(s), where discovery potential may be. This reflection must be addressed timely since each step in the field is worth decades (preparation and data-taking) and the subsequent large human and material resources. Indeed, addressing this reflection – to some extent – is the motivation of this document, where the potential for a missing piece is preliminary identified and still under study.

The PMNS Structure & Unitarity

This is one of the most critical questions to the field; arguably as important as the establishment of CP-violation in neutrino oscillations for which both DUNE and HK huge experiments are under consideration. However, while CP-violation is predicted in the neutrino oscillation framework (i.e. PMNS can

[3]This stands for the sign of Δm^2 since only vacuum oscillation has been used to measure it. Instead, the sign of δm^2 is well known due to matter dominated enhanced oscillations in the core of the sun as measured by solar experiments, where SNO and SK experiments are dominant.

be complex), there is no model whatsoever behind unitarity violation. Conversely, while there is no SM prediction for the CP-violation value, unitary prediction is granted by its definition. Hence, unitary explorations benefits the best direct discovery potential model-less framework exploiting an accurate SM prediction to identify deviations. Addressing unitary is complementary and synergetic to today's measurements of each parameter, regardless of the overall PMNS structure.

Indeed, in the following, we shall summarise, within the limitations of today's uncertainties, the main features of the PMNS matrix, illustrated in Fig.1. Its structure-wise description, beyond its parametrisation (or composition), offers some interesting features worth highlighting:

Why is PMNS so non-diagonal? Unlike the CKM, almost diagonal thus leading to minimal mixing in quarks, the PMNS is largely non-diagonal. This means its "off-diagonal" terms are large, as shown in Fig 1. This implies that whatever BSM theory stands behind the SM effective manifestation, the predicted flavour sector must be largely different for leptons and quarks. This is likely an important constraint for BSM modelling.

It is however striking to note that the θ_{13} is most peculiar. It is very small while drives the value of U_{e3}. Again, a possible hint from Nature suggesting that we ought to measure θ_{13} with the highest possible precision, as it might be key to understand the leptonic flavour sector. Ironically, no experiment today can improve 2010's results. Worse, today there is no experimental method known to be able to challenge those results. This however is addressed later on in this document.

Why is PMNS' J so large? The PMNS Jarkslog invariant (factorising out the CP-violation phase $\sin(\delta)$ term) is order $\sim 10^{-3}$, which is much larger than that of the CKM counterpart; order $\sim 10^{-5}$. This suggests that if the CP symmetry was violated ($\sin\delta \neq 0$), the expected CP violation amplitude will be large. This is an appealing scenario since we know the CP violation needed behind the observed matter to anti-matter asymmetry in the universe is many orders of magnitude too large compared to that embedded in the CKM.

Is PMNS unitary? As highlighted above, this is likely to be the ultimate and most challenging question that the neutrino oscillation phenomenon might allow us to explore. We shall address the possible implications and today's knowledge status below.

It seems clear that PMNS structure seem to "speak a different language" from that suggested by the CKM. Hence, their nature may likely be different, although unknown. For some, the PMNS bizarreness (compared to CKM) might indicate that its most precise exploration and scrutiny is one of the best ways to challenge the SM. Indeed, it would not be the first time neutrinos proved our best probe to BSM phenomenology. One of the latest modifications in the SM was the introduction of the phenomenology of massive neutrinos, as inferred from neutrino oscillations, although the absolute scale of their lightness remains a challenging mystery.

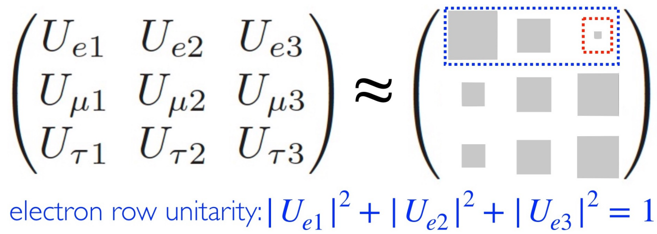

Figure 1: **The PMNS Neutrino Mixing Matrix.** The highly non-diagonal structure and main features of the PMNS matrix are illustrated. The overall PMNS unitarity test can be reduced to test the unitarity of the rows, where the most sensitive test arises from the *electron row* (indicated in blue). One of the most peculiar features is the smallness of the U_{e3} term (indicated in red). This terms corresponds to the pure value of θ_{13}, if unitary.

To address the PMNS unitarity, we need the world-wide sub-percent mixing precision. The results from JUNO, DUNE and HK are therefore critical. However, those are necessary but not evidently sufficient conditions to yield the needed insight. Testing for the PMNS unitarity implies abandoning the three mixing angles (θ_{13}, θ_{12}, θ_{23}) approximation. This means equations must be expressed in terms of their U_{ij} terms upon imposing the unitary condition (i.e. $UU^\dagger = I$). This translates experimentally into constraining more equations. However, the number of independent observables measured by the different experiments is not scaling alike. So, **to test unitary to the percent level implies the need for the above described increase in precision but also additional measurements by 2030**. This is described below. Indeed, only within 2020, the field is nearing readiness, for the first time, to address this question at a competitive level of precision. The reward of addressing this question is remarkable: **any significant evidence for non-unitarity implies the manifestation, and thus discovery, of non-standard neutrino states and / or interactions** [15]. Non-standard interactions (**NSI**) [16] stand for deviations from the standard V-A weak interaction model for neutrinos. This implies direct sensitivity to BSM physics despite lacking any established model behind. Given the stunning prediction power demonstrated by the SM to all so far tested observables, such as in LHC, there is a diminishing phase space for direct access to discoveries in particle physics with today's technology. Hence, testing the PMNS unitary is indeed a compelling and unique opportunity. In addition, by doing this we will coherently address all SM known quantities with maximal complementary.

The PMNS Unitarity Test Strategy

Solving the unitary condition ($UU^\dagger = I$) leads to 12 equations [17]. Some are equivalent to testing the "closure of triangles" in the CKM case, should the CP violation be known. Since, the neutrino CP violation is unknown, the PMNS unitary condition can be tested today via the derived $|U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1$ condition, with $l = e, \mu, \tau$. These equations test the unitarity of each matrix row. Only the e and μ are considered since τ related oscillations are less constrained. In fact, the most stringent constraint arises from the *electron-row unitarity* (**ERU**)[4] (or top row) leading to $|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$ accurate condition. If unitarity held, this row depends only on θ_{13} and θ_{12}. Hence, any experiments with the ability to constrain θ_{13} and/or θ_{12} is of critical impact. ERU is the only direct and most precise access to unitarity [15, 17], likely even after 2030 experiments.

This is excellent news for JUNO whose highest sensitivity to θ_{12} (also δm^2)[5] unprecedentedly grants some of the necessary sub-percent precision to test ERU. Indeed, JUNO is one of the most important experiment in the unitarity quest [12]. However, that is not good enough. Since, it is difficult to foresee any improvement on JUNO, even in the far future, we need more high precision measurements elsewhere. Hoewever, the sensitivity on θ_{13} appears not improvable in foreseeable future, as highlighted before. As discussed in [15, 17], testing for ERU implies several experimental constraints:

Via δm^2 Oscillations (θ_{12}, if unitary): JUNO measures $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ with reactor neutrinos over a ~50 km baseline. Also, solar neutrinos have key information by probing $P(\nu_e \rightarrow \nu_e)$ in the core of the sun via matter effects. Today's best constraints are SNO and SK, but there is no dedicated solar experiment foreseen in the future, with JUNO having some marginal sensitivity.

Via Δm^2 Oscillations (θ_{13}, if unitary): again reactor experiments, like DC and DYB, had measured $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ at the baseline of ~1.5 km. There is however no known ν_e source[6] capable of addressing $P(\nu_e \rightarrow \nu_e)$ precisely enough with a compatible L/E ratio.

Although not highlighted explicitly above, the ***absolute flux* knowledge** is also of critical impact to test ERU [15, 17]. However, the control of the absolute flux uncertainties is experimentally very challenging. This is indeed why many neutrino oscillation experiments use multi-detectors to bypass absolute systematics, as opposed to the simpler relative systematic basis. This way, for example, DC systematics can be controlled to the few per mille level while the absolute is controlled to order a few % at best. Worse, reactor neutrinos have evidenced a non-understood deficit [18] (2011) and spectral distorsion [19] (2014) relative to ILL-data based predictions. This could be interpreted as a hypothetical manifestation of non-standard neutrinos with Δm^2at $\sim 1\,eV^2$. Today however such a hypothesis has lost much ground thanks to new data addressing this issue directly (i.e. ruling out the pertinent hypothetical phase-space) [2] and/or indirect (i.e. demonstrating that the reactor prediction uncertainties are likely larger) [4]. Considering all those effects, today's studies [15, 17] suggest that the ERU test can be at the few percent (>2%) precision even with JUNO. A dedicated experimental effort addressed to yield maximal sensitivity to unitarity is discussed next, whose ongoing quantification impact is not yet completed. The goal is to articulate unitarity test precision to the sub-percent level, if possible.

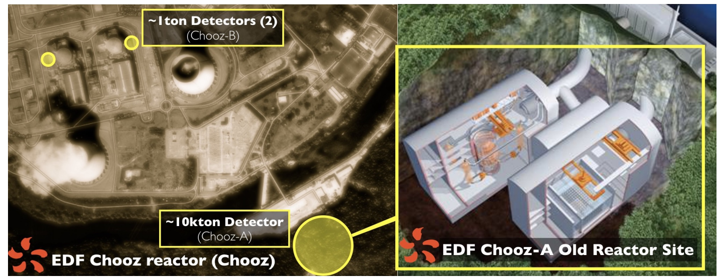

Figure 2: **The Super Chooz Site.** The SC experiment relies on two very-near detectors (order 1ton each) and one far large detector (order 10 kton). The multi-purpose far detector provide most of the physics programme (see text). The site relies on the scientific use of one of the old Chooz-A reactor caverns, provided by EDF, as an effective expansion of the existing LNCA laboratory.

Need & Exploration for Super Chooz

Improving ERU test precision beyond JUNO requires (a) a significantly better measurement of θ_{13} (ideally sub-percent precision), (b) a much better control of absolute flux and, possibly, (c) a better measurement of solar neutrinos. Unfortunately, all those items are considered today either impractical – or even impossible – with today's technology.

However, a new neutrino detection technology pioneered in the CNRS/IN2P3 call **LiquidO** [20] might allow to address all those questions – maybe even in single experimental site. This was first proposed and presented in July 2019 in the *HEP-EPS conference* [21] where the potential of a hypothetical **Super Chooz** (**SC**) project was preliminary highlighted. The project would rely on an ~10 kton LiquidO detector located in one of the existing new caverns upon the final deconstruction of the old Chooz-A reactor site. These caverns are to become available by >2025 under EDF property, implying minimal civil construction. This implies that the existing LNCA laboratory (Chooz) could expand to become one of the largest underground laboratories in Europe with two of the most powerful Areva N4 reactors in the world as source.

While the physics potential study is still ongoing, the final performance depends on the LiquidO performance, still under intense demonstration effort despite encouraging first proof of principle [20] using its first opaque scintillator articulation [22]. An important necessary result has been demonstrated: the θ_{13} measurement to <1% is possible [21] – publication soon. This is a breakthrough in itself since no technique so far is known to be able to reach such a precision. However, again, this is one of the necessary conditions to improve ERU test. This potential drives the above mentioned detector size and the need for LiquidO technology[7]. A novel technique called *reactor flux decomposition* is also proposed in [21] for total reactor flux error cancellation, also demonstrating that the near detector technique, a la DC or DYB, is insufficient. Our studies suggest the word best precision on

[4] The *μ-row* case precision is limited by several experimental uncertainties such the absolute flux (typically few % in neutrino beams) and the unresolved atmospheric mass ordering and the "octant" ambiguities due to the maximal (or almost) value of θ_{23}.

[5] A team led by CNRS/IN2P3 members (LAL/SUBATECH) have developed a dedicated strategy for the measurement of θ_{12} and δm^2using a dual-readout approach. This approach is expected to yield novel and unique redundancy proposed originally by the CNRS/IN2P3 team.

[6] The only possible exception is π/μ decay-at-rest using an accelerator beam-dump or alike. However, this suffers other complications/limitations.

[7] LiquidO has unique capability to strongly reduce cosmogenic backgrounds (event-wise ID) and control both energy and detection systematics.

both θ_{13} and Δm^2via shape extraction. Hence 2 (out of 6) of the parameters listed in Table 1 are to be best measured in SC. The SC experimental configuration is shown in Fig 2. However, the SC can also address the two other measurements needed for the world best unitarity precision:

Reactor Neutrino Absolute Flux. The reactor flux decomposition technique alluded before implies the need for small LiquidO detectors at ∼20 m from each reactor [21]. They could provide the most precise reactor flux rate measurements – ongoing study. New techniques are likely needed and under consideration. This is complementary to the JUNO [23] best reactor spectral reference using the dedicated TAO detector.

Solar Neutrino Measurement. Upon indium loading [20], SC might allow unprecedented solar neutrino measurement via CC interactions, unlike electron elastic scattering. The main challenge is to be able to handle cosmogenic backgrounds due to the lower overburden. LiquidO's μ precise tracking is expected to allow for unprecedented tagging between the primary μ and the spallation products. With JUNO's measurements of δm^2 and θ_{12}, solar neutrinos would allow further constrain of the unitary test as well as probing both sun physics and NSI at the longest possible baselines, hence expanding SC scope to BSM searches. This scenario is also under active ongoing study.

Beyond the main goal of unitarity test, SuperChooz measurements of θ_{13} and Δm^2 would enhance the sensitivities of all of the forthcoming experiments. The sensitivity of CP violation by DUNE+HK and JUNO's mass ordering are expected to improve from both such inputs. The quantification of this critical synergy is ongoing.

Furthermore, SuperChooz could also become one of the best supernova neutrino (burst & remnant) and proton decay in the world, while complementary to other foreseen detector. On the supernova side, the ability for LiquidO to detect and identify $\bar{\nu}_e$ and ν_e, upon CC interactions, allows unique capability for supernova neutrinos (<50 MeV), including major background reduction. Flavour independent NC interaction detection is also possible upon loading, as highlighted in [20]. The supernova potential is under active ongoing study. On the proton decay channel, LiquidO's event-wise imaging allows the identification of K^+, π^0, $\pi^\pm$, $\mu^\pm$, etc. via their main decay mode(s), where all of those particles play a role in different proton decay modes. Thus, LiquidO is expected to be one of the best proton decay searches technologies in terms of its highest free-proton density (normal in scintillators), high efficiency of detection and multi-decay mode sensitivity, boosted by its expected large background rejection. This was preliminary highlighted in [24]. The feasibility and vast physics program of a hypothetical SuperChooz, based in France, is under study by the LiquidO collaboration, as well as several other cooperating institutions, putting together experimentalists and phenomenologists word-wide for this exploration. The SuperChooz project has the potential for unique breakthrough role in field, should LiquidO performance demonstrates. The SuperChooz feasibility and full physics program is expected clarified within the 2020 decade.

Prospect Discussion & Conclusions

We hereby highlight and propose active study for a coherent experimental path towards high precision PMNS unitarity physics. This is one of the most important fundamental SM building-blocks observable within the neutrino oscillation framework. Unitary is likely the only existing probe within the neutrino oscillations framework with direct sensitivity to BSM physics, as it may evidence for non-standard neutrino interactions and/or states, including a existence of a hypothetical 4th family beyond the kinematical limitations. This implies open ground for discovery beyond any established theory. The sensitivity to unitarity is boosted by the next generation projects JUNO, DUNE and HK, where JUNO is likely the main highlight. Hence, we here draw a coherent strategy flowing from today's culminating effort (DC, SOLiD [25], STEREO [26]) towards JUNO (under construction), whose sub-percent measurements are of strong value to the unitarity exploration. Unfortunately even with JUNO, the world data do not allow yet to yield the sub-percent level in unitarity sensitivity. We therefore need still other complementary measurements, as highlighted, not foreseen so far. We thus identify and profile, for the first time, the need for a new experiment, here called preliminary **Super Chooz** (SC). SC is designed to target the PMNS unitarity with maximal direct sensitivity, including existing data. Its challenge is to attempt to address all the needed measurements for unitarity in one single experiment, if possible. Its final sensitivity is under ongoing quantification for publication soon.

Besides the θ_{13} most peculiar role in the PMNS structure, its knowledge is one the most important elements to test unitarity. As of today, there is no experiment – or even a known technique – capable to improve the existing 1.5% precision, thus going from today's best known to the worst known by 2030. SC has been designed to uniquely yield the most precise measurements on both θ_{13} and Δm^2 in history. SC has also the potential to address an improvement in absolute flux control. Both cases are under finalising studies as well as their direct impact to the unitarity sensitivity. Additionally, SC gears a unique synergy with JUNO, DUNE and HK thus reinforcing their CP violation and mass ordering sensitivities – both known to enhance with the most precise θ_{13} and Δm^2.

The SC project relies on LiquidO detection, pioneered by CNRS/IN2P3, whose cosmogenic rejection is critical for low overburden. The SC concept strategically combines the unique opportunity to reuse the EDF multi-kiloton cavities (available from ∼2025) thus expanding the LNCA laboratory (Chooz) into one of the largest underground facilities in Europe. Thus, SC may imply a world leading facility enlarging the European neutrino fundamental research, based in France, under the leadership of CNRS/IN2P3, thus boosting its excellence in the field. The potential of SC is under exploration by the LiquidO international collaboration, also led by CNRS/IN2P3 teams. A hypothetical SC envisages a time scale >2025, thus incurring no conflict whatsoever with any existing experimental programs. Conversely, SC is expected to coherently enhance the physics yield and prospect of all today's CNRS/IN2P3 neutrino programs. Last, the SC proposed science matches in full today's APPEC roadmap [27].

References

[1] NuFIT 4.1. [www.nu-fit.org.] (2019) JHEP 01 106 (2019)
[2] Giunti C. *et al.* JHEP 1710 143 (2017),
Dentler M. *et al.* JHEP 10.1007 010 (2018)
[3] SK Collab.(Fukuda Y. *et al.*) Phys.Rev.Lett. 81, 1562 (1998)
SNO Collab.(Ahmad Q.R. *et al.*) Phys.Rev.Lett. 89, 011301 (2002)
KamLAND Collab.(Eguchi K. *et al.*) Phys.Rev.Lett. 90, 021802 (2003)
[4] DC Collab.(de Kerret H *et al.*) Preprint at arXiv: 1901.09445
[5] DYB Collab.(An F. *et al.*) Phys.Rev.D 95 7 072006 (2017)
[6] RENO Collab.(Bak G. *et al.*) Phys.Rev.Lett. 121, 201801 (2018)
[7] Particle Data Group (Tanabashi M. *et al.*) Phys. Rev. D 98 030001 (2018)
[8] SK Collab.(Jiang M. *et al.*) Preprint at arXiv: 1901.03230
[9] T2K Collab(Abe K. *et al.*) Phys. Rev. Lett. 118 15, 151801 (2017)
[10] IceCube Collab.(Aartsen M. G. *et al.*) Preprint at arXiv: 1401.2046
[11] ORCA Collab.(Adrián-Martínez S.) J.Phys. G43 8 084001 (2016)
[12] JUNO Collab.(An F. P. *et al.*) J. Phys. G43 3 030401 (2016)
[13] DUNE Collab.(Acciarri R *et al.*) Preprint at arXiv: 1512.06148
[14] HK Collab.(Abe K. *et al.*) PTEP 2015 053C02 (2015)
[15] Fong C. S. *et al.*. Preprint at arXiv: 1609.08623
[16] Y. Farzan and M. Tórtola. Preprint at arXiv: 1901.09445
[17] Qian X. *et al.*. Preprint at arXiv: 1308.5700
[18] Mueller T. *et al.* Phys.Rev.C 83 054615 (2011)
Huber P. Phys. Rev. C 85 024617 (2011); 029901(E) (2012)
Schreckenbach K. *et al.* Phys.Lett.B 160 325 (1985)
von Feilitzsch F. *et al.* Phys.Lett.B 118 162 (1982)
Hahn A. *et al.* Phys.Lett.B 218 365 (1989)
[19] DC Collab.(Abe Y *et al.*) JHEP 10 086 (2014)
Erratum: JHEP 02 074 (2015)
[20] LiquidO Collab.(Cabrera A *et al.*) Preprint at arXiv: 1909.02859 (August 2019)
[21] Cabrera A *et al.* HEP-EPS Conference Talk (July 2019)
Web: *https://indico.cern.ch/event/577856/contributions/3421609*
[22] Buck C. *et al.* Preprint at arXiv: 1908.03334
[23] JUNO Collab.(Cao J.) Technical Meeting on Nuclear Data for Anti-neutrino Spectra and Their Applications. IAEA (2019)
[24] Cabrera A *et al.* CERN Detector Seminar (June 2019)
Web: *https://indico.cern.ch/event/823865*
[25] SOLiD Collab.(Abreu, Y. *et al.*) JINST12 04 P04024 (2017)
[26] STEREO Collab.(N. Allemandou *et al.* JINST 13 07 P07009 (2018)
STEREO Collab.(L. Bernard *et al.*) Preprint at arXiv: 1905.11896
[27] APPEC: "European Astroparticle Physics Strategy 2017-2026" (August 2017)

Acknowledgment

We would like to thank Prof. Hiroshi Nunokawa (phenomenologist at the PUC University Rio de Janeiro, Brazil) for rich discussion about the unitarity phenomenology in an ongoing collaboration with several experimentalists. Prof. Nunokawa is expected to come to LAL (Orsay, France) in sabbatical from fall 2019. We also would like to thank the LiquidO collaboration (20 institutions over 10 countries) for their fruitful discussion on the topic and the leading studies on the SuperChooz potential. The sensitivity to the θ_{13} was led by J.P. Ochoa Ricoux and B. Roskovec (University of California Irvine, USA), T. J. C. Bezerra and F. Yermia (SUBATECH, France) and A. Cabrera (LAL, France) The solar neutrinos physics and impact is under preliminary study by A. Cabrera (LAL, France), M. Chen (Queen's University, Canada) and Carlos Pea Garay (IFIC, Spain). Finally, the sensitivity supernova remnant is carried out as collaboration with IFIC (Spain) phenomenologists, Pilar Coloma and Olga Mena, following previous studies within the LiquidO collaboration.