Contribution Prospectives 2020

The European Spallation neutrino Super Beam

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Abstract:

It is believed that after the Big Bang matter and antimatter were produced in equal quantities through transformation of the enormous energy released into massive particles. Observations show that today, however, there is a nearly total absence of antimatter in the Universe. The occurrence of Charge-Parity Violation (CPV) is a necessary condition for an explanation of this absence. CPV has already been observed in the quark sector but the measured amount is insufficient to explain the observed matter-antimatter asymmetry. The discovery of neutrino CPV becomes an important candidate to explain the observed matter dominance in the Universe. The goal of the ESSνSB project is to prepare the ground to discover and measure neutrino CPV with unprecedented sensitivity.

The ESSνSB concept takes advantage of two outstanding opportunities. The first is the construction in Europe of the European Spallation Source, ESS, which will have world's most intense proton beam, with a power a factor of five higher than any other currently existing or planned accelerator. The second is the measured unexpectedly large value of the oscillation mixing angle θ_{13}. This implies that, to obtain maximum sensitivity to CPV and thereby be less affected by systematic uncertainties, the neutrino far detector should be placed at the second neutrino oscillation maximum. The Garpenberg mine in Sweden, in which it is proposed to install the underground Water Cherenkov neutrino detector of ESSnuSB, is situated at a distance of 540 km from ESS that corresponds to the second maximum.

Calculations shows that the proposed facility can cover up to 60% of the CPV parameter δ_{CP} with a significance of more than 5σ in ten years operation. This performance is obtained with very reasonable systematic error assumptions, as 5% on the signal and 10% on the background, which they are at the level of what T2K is about to obtain. After ten years of operation, the results will still be dominated by the statistical errors, in which case, if more precision is needed, it would just be enough to continue taking data without any further investment.

This project is now financed by the EU through the H2020-INFRADEV-1-2017 Design Study. This study, of a total cost of 4.7 M€ of which 3 M€ are provided by EU, has started its activities in January 2018 and will last for four years. 15 institutions participate to this project, among them the CERN and the ESS. **The project is coordinated by the CNRS**. A Conceptual Design Report, including a construction timeline and indicative capital costing, will be provided by the end of the Design Study. This study will also identify areas where R&D will be needed. At the end of the Design Study, by 2022, R&D projects will be submitted. For this reason, it is important this project to be part of the next European Strategy.

Furthermore, the COST Action EuroNuNet (CA15139) also **coordinated by the CNRS**, "*Combining forces for a novel European facility for neutrino-antineutrino symmetry-violation discovery*", supports this project and recognizes the necessity to have at least one neutrino facility in Europe.

Together with the neutrino production, a copious number of muons will also be produced. At the level of the proton beam dump (25 m away of the target station), more than $5x10^{21}$ 0.5 GeV muons can be extracted and used by other facilities. These facilities could be a low energy nuSTORM, a Neutrino Factory or a muon collider in the far future. This shows the great potential of the ESSnuSB project.

1 Context

1.1 The new possibility to discover and measure CP violation in the leptonic sector

The discovery in 1998 of neutrino flavour oscillations opened up the possibility that there be CP violation in the leptonic sector and that this CP violation could be discovered and measured through precision measurements of the oscillations. The oscillation that is potentially the most sensitive to CP violation is $\nu_\mu \rightarrow \nu_e$. The oscillation probability is approximately equal to the sum of three terms, the *atmospheric*, the *solar* and the *interference* term, see Figure 1[1]. The observation of a CP violating signal requires the interference term to be of measurable magnitude.

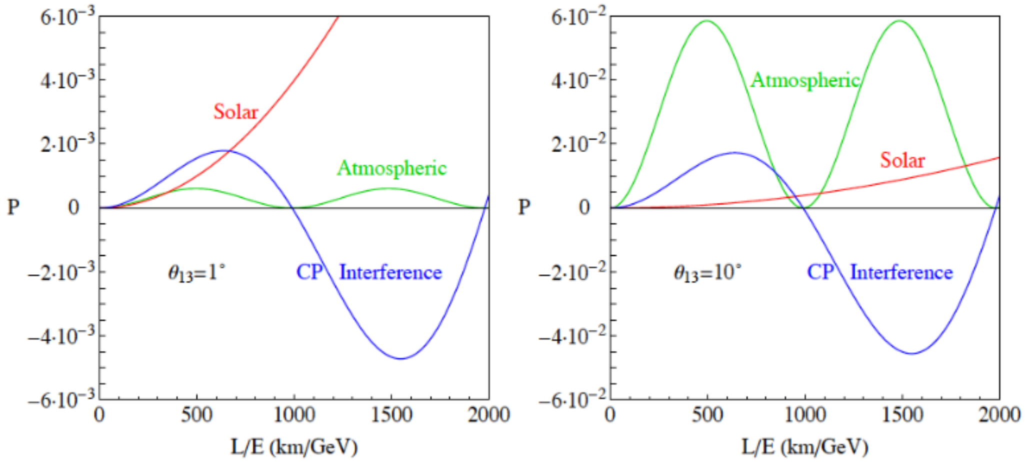

Figure 1: Solar, atmospheric and interference terms of the $\nu_\mu \rightarrow \nu_e$ oscillation in vacuum as function of L/E for a small (left) and a large (right) θ_{13} value.

The atmospheric term increases with the angle θ_{13} while the solar term increases with L/E where L is the distance between the creation point of neutrinos and the detector and E the neutrino energy. In order to maximize the interference term, and thus the CP violation signal, these two terms should be of similar magnitude. Before 2012 the value of θ_{13} had not been measured, but it was thought to be very small, implying that to have the two terms of similar magnitude, the L/E ratio should be approximately 500 km/GeV, corresponding to the position of the first oscillation maximum, as illustrated in the left plot of Figure 1.

In 2012 the reactor experiments published results of measurements of the mixing angle θ_{13} of around 9˚. This relatively large value opened up the possibility to measure the CP violating parameter δ_{CP} (CP is violated if the value of δ_{CP} is neither 0 nor π). Moreover, to compensate for the unexpectedly large value of θ_{13}, the value of L/E needs to be increased by approximately a factor 3, which is realized by relocating the detector from the first to the second neutrino oscillation maximum, at which the atmospheric and solar terms are of the similar order as illustrated in the right plot of Figure 1. This type of optimization under the new paradigm of a large θ_{13} value is crucial in order to obtain the interference term as high as possible, thereby avoiding to be severely limited by the systematic uncertainties of the other two terms. The ESSνSB setup already incorporates this novel feature: the 540 km baseline and ca 0.35 MeV mean energy of the neutrino energy of ESSνSB implies an L/E value of 1500 km/GeV centred at the second oscillation maximum. Moreover, the asymmetry between the neutrino and anti-neutrino appearance probability at the second oscillation maximum is of the order of $0.75\sin\delta_{CP}$([2]) while on the first oscillation maximum is only $0.30\sin\delta_{CP}$. For these reasons and considering the limitations imposed by systematic errors, the ESSνSB setup provides a better sensitivity to CP violation than similar setups which were designed before 2012 to have their neutrino detector placed at the first oscillation maximum and which have not been able to re-optimize their experimental design subsequent to the discovery of the large value of θ_{13}.

While current neutrino oscillation facilities such as T2K and NOvA may develop some sensitivity to δ_{CP}, which for T2K currently is at the 2 to 3 standard deviations level, new experimental facilities with more powerful accelerators and larger fiducial-mass neutrino-detectors will be necessary for their discovery at the 5 σ level.

[1] P. Coloma, E. Fernandez-Martinez, JHEP 1204 (2012) 089, DOI: 10.1007/JHEP04(2012)089, e-Print: arXiv:1110.4583 [hep-ph]

[2] S. Parke, Phys.Scripta T158 (2013) 014013, FERMILAB-CONF-13-453-T, DOI: 10.1088/0031-8949/2013/T158/014013

As to the future experiments Hyper-K and DUNE, proposed already before 2012, they were designed under the assumption of a very small value of θ_{13}, for which case the relative CP violation signal at the fist oscillation maximum would be significantly larger than at the second. For the now known larger value of θ_{13}, the situation is thus reversed. This now implies, for equal performance at the first and the second oscillation maximum, the requirement of significantly smaller systematic errors when measuring at the first maximum as compared to the second. In order to keep the statistical errors on a level comparable to the systematic errors, a very intense neutrino beam is needed for the measurement at the three times more distant second oscillation maximum. With ESSνSB this requirement is satisfied by the use of what is to become the world's most powerful proton accelerator, the European Spallation Source linear accelerator (linac)[3].

1.2 Performance for CP violation discovery

In Figure *2* is presented the physics performance of the three different proposed long baseline neutrino experiments **assuming the same level of systematic errors of about 3% for all three in order to make a comparison on an equal footing**. The left plot shows the resolution in the measurement of δ_{CP} versus the value of δ_{CP}, the middle plot shows the discovery significance for CP violation versus δ_{CP}, and the right plot the significance as function of the covered fraction of δ_{CP}. In the figure caption more details about the plots are given. These plots clearly demonstrate that ESSνSB has a higher resolution in the measurement of the CP violating angle δ_{CP} and a large reach for CP violation discovery than the other two experiments, covering up to 75% of δ_{CP} values at 5 σ significance. This high performance of ESSνSB over other projects becomes more important if higher systematic errors are assumed. Indeed, the assumption of 3% systematic error on the signal is very optimistic. 5% is more reasonable, knowing that T2K, after 10 years operation, only reached the level of 6-7% systematic error.

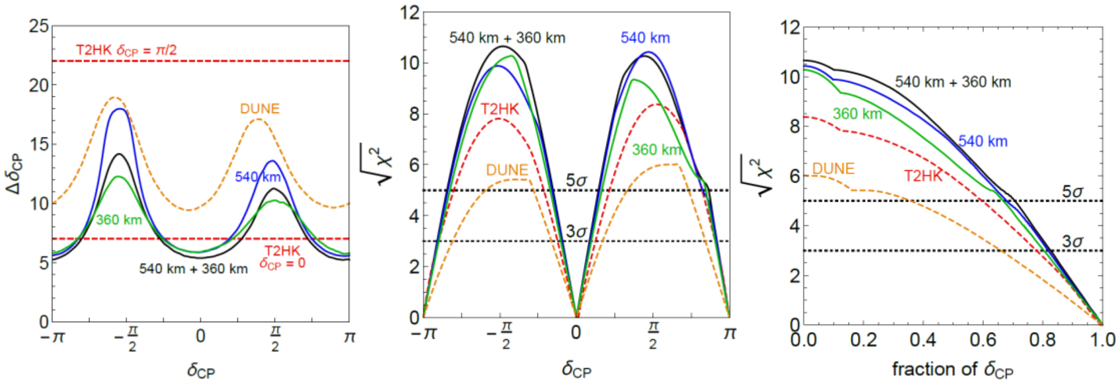

Figure 2: Resolution in angle δ_{CP} (left), the CP violation discovery reach versus δ_{CP} (middle), and the discovery reach versus the fraction of the δ_{CP} range covered (right), for the three different experiments Hyper-K, DUNE and ESSνSB. For the ESSνSB three cases are shown, one 500 kt detector in the Garpenberg mine (540 km baseline, blue curves), one 500 kt detector in the Zinkgruvan mine (360 km baseline, green curves) and two 250 kt detectors, one in the Garpenberg mine and one in the Zinkgruvan mine (black curves).

1.3 The ongoing construction of the ESS linac

The ESS linac will have an average beam power of 5 MW, which is nearly 5 times higher than any other currently operating proton accelerator in the world. It will deliver a beam of 2 GeV protons to a Tungsten target to produce neutron beams from spallation. ESS is currently well into its construction phase and will deliver first beams in 2021 and be at full specification in 2025. It will be a major European user facility where researchers from universities, national laboratories and industry from all the world will investigate scientific questions relating to material science, molecular biology and other sciences.

2 Objectives

2.1 The precision measurement of the CP violating angle δ_{CP}

The implications of the discovery and precise measurement of δ_{CP} are far reaching, leading to the inference that neutrino interactions may in fact be responsible for that a small residual fraction of matter survived the

[3] The European Spallation Source, http://europeanspallationsource.se/, *ESS Technical Design Report*, Release 1.0, Nov. 2012.

massive annihilation of the matter and antimatter created in the Big Bang, a residual that is what presently makes up the matter of the Universe. The neutrino may also have played a crucial role in the birth and evolution of the Universe itself, in view of its enormous abundance. An understanding of the contribution of neutrinos in these areas requires precise measurements of the parameters governing neutrino oscillations, in particular δ_{CP}.

A measurement of δ_{CP} could also imply the discovery of a completely new source of CP violation. The quark mixing matrix provides a consistent description of the quark CP violation amount observed so far, which can be encoded in the reduced Jarlskog invariant $J = (3.0 \pm 0.2)\cdot 10^{-5}$. This value has been shown to be far too small to account for the observed Baryon Asymmetry of the Universe (BAU). The recent measurement of θ_{13} indicates that the corresponding quantity in the neutrino sector J=0.3·sinδ_{CP} is potentially four orders of magnitude larger. A measurement of δ_{CP} could thus, as already discussed, provide very illuminating information on the origin of the BAU.

2.2 The measurement of supernova neutrinos and search for proton decay

The MEMPHYS detector can also be used, simultaneously with neutrino beam operation, for astroparticle physics. In 1987, 12 neutrinos emitted from a supernova explosion in the Large Magellan Cloud near our galaxy were detected by the Kamiokande detector. Such detection helps to understand the supernova explosion mechanism. With its 500 kton large fiducial mass, the MEMPHYS detector will record about 5×10^4 neutrinos from a supernova explosion at 10 kiloparsec distance in our galaxy which would provide very detailed and highly interesting information on the mechanism of the explosion.

The MEMPHYS detector can also be used for proton lifetime measurements. Proton decay is not allowed by the SM. On the other hand, Grand Unified Theories (GUT) predict proton decay. Its discovery would once again reveal the existence of a more fundamental theory beyond the SM. The present lower limit of the half-life for the decay $p \rightarrow \pi^0 e^+$ is 1.6×10^{34} years set by Super-Kamiokande employing the same Water Cherenkov detector technique as ESSνSB is planning to use, but with a detector volume 20 times smaller than MEMPHYS. If the proton life-time is below 10^{35} years, then proton decays would be observed after 10 years of data taking with MEMPHYS. If not, on the other hand, no proton decays would be observed, this would impose a stringent limit on GUT.

3 Methodology

3.1 The ESS linac upgrade required to deliver a 2x5 MW beam

In order to achieve a sufficiently intense neutrino beam a proton beam of about 5 MW average power will be required. The ESS linac will be used to accelerate protons to the energy of 2 GeV in 2.86 ms long pulses at 14 Hz pulse frequency to be used for spallation neutron production. The low duty cycle of 4% of the ESS linac makes it possible to accelerate additional pulses of H^- ions, interleaved with the proton pulses, to be used for the proposed production of a uniquely high-intensity neutrino beam.
The modifications that will have to be undertaken to increase the ESS linac power from 5 MW to 10 MW, have been studied by F. Gerigk and E. Montesinos and documented in a CERN report[4]. The conclusion of the authors is that "*no show stoppers have been identified for a possible future addition of the capability of a 5 MW H^- beam to the 5 MW H^+ beam of the ESS linac built as presently foreseen*." The proposed modifications are studied now in more detail by the current Design Study.

3.2 The development of an accumulator ring

The very high current (350 kA) pulse needed in the hadron collector (magnetic horn) that focuses the produced pions in the forward direction causes a high heat dissipation in the thin walls of the hadron collector. The flat top of the current pulse can for this reason not be longer than the order of a few µs. The 2.86 ms length of the pulses from the ESS linac will therefore be compressed by about three orders of magnitude to about 1.3 µs using a 400 m circumference accumulator ring.

As a first step in the design of this ring, the magnetic lattice of the accumulator ring of the US Spallation Neutron Source (SNS) in Oak Ridge, USA, has been adapted to the higher energy of the ESS beam, using

[4] CERN-ACC-NOTE-2016-0050 (2016)

simulations to study different H^- stripping schemes and the accumulator beam stability including space charge effects. The beam transfer line from the linac to the accumulator, the multi-turn injection, including the H^- stripping system and the extraction kicker for single turn ejection, will be developed.

Spallation neutron users of the ESS have expressed a keen interest in having pulses significantly shorter than 2.86 ms, like 100 µs long pulses. Such pulse could be achieved with the proposed accumulator ring using slow extraction, an option that will be included in the present Design Study. The synergy between the two uses opens up the perspective of sharing the investment and operation costs for the H^- beam and the accumulator with the neutron users.

3.3 The Target Station for a 5 MW proton beam for neutrino production

The Target Station includes the proton target itself, the hadron collector, the decay tunnel and the beam dump. The design of a target for neutrino production capable of withstanding the heat load of a 5 MW beam seems not feasible. In order to reduce the heat-load there will be four targets, which will be hit in sequence by the proton pulses, thereby reducing the beam power hitting each target to 1.25 MW. Following the EUROν studies[5], a packed bed of titanium spheres cooled with helium gas has become the baseline design for a Super Beam based on a 2-5 GeV proton beam with a power of up to 1.3 MW per target.

The Target Station includes a ca 25 m long decay tunnel and a beam dump. Particular care will be taken in the design of these elements to preserve a possible future utilisation of muons produced at the same time as the neutrinos for other facilities such as low-energy nuSTORM, a Neutrino Factory and/or a muon collider.

3.4 The Near and Far Detectors

A Near Detector located in the beam a few hundred meters downstream from the target station is required to monitor the neutrino flux, to measure neutrino cross sections and to study background channels. For ESSνSB the study of cross sections will be particularly important as there are till now very few such measurements for the relatively low neutrino energies 0.2-0.6 GeV of the ESSνSB beam. The relatively high beam flux of the ESSνSB beam at the level of the Near Detector will make high statistics measurement of the neutrino cross-sections feasible.

The Far Detector shall detect and identify the ν_μ and, in particular, the ν_e and provide a measurement of their energy with an as large as possible fiducial target mass. The starting point for the ESSνSB Far Detector design is the detailed MEMPHYS detector designed and evaluated by the EUROν and LAGUNA EU projects. This detector has 500 kt fiducial mass divided up on two cylindrical detector volumes, 65 m in diameter and 100 m high. The Garpenberg mine, located at 540 km from ESS, is currently the prime candidate location for the MEMPHYS type detector of ESSνSB (1000 m depth). The Zinkgruvan mine, located at 360 km from ESS, is the second option for the location of the Far Detector. Zinkgruvan mine is, like Garpenberg, located near the second oscillation maximum and approximately on the same straight line from ESS as Garpenberg. In Figure *2* are shown the performance with both MEMPHYS detector cylinders in Garpenberg, with one of the detector cylinders in Garpenberg and one in Zinkgruvan and with both detector cylinders in Zinkgruvan. The CP violation discovery reach is similar for the three cases where as the resolution in δ_{CP}, is higher for Zinkgruvan compared to the other two.
As to the design of the Far Detector photo-detectors, more efficient and less costly designs, like that of the MCP photomultipliers produced for JUNO, have appeared on the market, replacing the classical Venetian-blind-dynode-amplified photomultiplier and making a higher photo-detection efficiency and larger photodetector coverage possible with no increase in detector cost.

4 Readiness

The concept of using the ESS linac to generate a uniquely intense neutrino beam to enable measurements at the second oscillation maximum was first presented in a seminar at CERN in 2012. In 2015 the ESSνSB consortium received a ca 0.3 MEUR allocation from the EU COST Association for the period 2016-2020 to set up a European network, EuroNuNet[6], with the purpose of "Combining forces for a novel European facility for

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[5] *A High Intensity Neutrino Oscillation Facility in Europe,* EU FP 7 Design Study: EUROnu, Project No. 212372
[6] https://www.cost.eu/actions/CA15139#tabs|Name:overview

neutrino-antineutrino symmetry-violation discovery". The COST grant is currently used for financing travel and scientific missions of neutrino scientists between the 13 participating countries.

In 2017 the ESSνSB consortium received 3 MEUR funding from the H2020 program to finance a Design Study of a total cost of 4.7 M€, during the period 2018-2021[7]. The 15 member institutions of the ESSνSB H2020 INFRADEV-1 Design Study are given in annex. **The ESSνSB Design Study is coordinated by CNRS**. A significant fraction of the ESSνSB funding is being used to recruit and finance young postdocs to contribute in the design work. The results of the now ongoing Design Study will be published in a Conceptual Design Report (CDR) end of 2021.

The plan is that the ESSνSB INFRADEV-1 Design Study 2018-2021 will be followed by an R&D period, 2022-2025. As from 2025 (end of ESS neutron facility), financial support from European governments to enable the start of ESSνSB construction work before the end of next decade will have to be found. It is foreseen that the build-up of the neutrino production infrastructure at ESS and the neutrino detector will be going on for ca 7 years leading up to the start of data taking some time in the period 2035-2036. A first task for ESSνSB will be to discover leptonic CP violation and measure δ_{CP} with high precision. In subsequent updates and according to the physics needs, this neutrino Super Beam could be transformed to a **muon facility** to serve a Neutrino Factory or/and a muon collider.

5 Expected challenges

5.1 The handling of the very high-power H^- beam in the linac

The particles to be accelerated in the ESS linac and injected into the accumulator will be H^- ions. If the two electrons of the H^- are lost due to different kinds of perturbations in the accelerator and beam transfer line from the H^- ion source to the accumulator injection point, the resulting proton will hit the beam pipe walls of the linac and transfer line and induce radioactivity in the surrounding equipment. Currently, a proton beam loss of 0.1 W/m is foreseen for proton acceleration in the linac. An increase in the loss of up to 1 W/m due to increased beam loss with H^- acceleration and transfer could be tolerated. There are however a number of conditions on the linac and the transfer line that need to be fulfilled to avoid a higher loss. These conditions are being carefully studied.

5.2 ESSνSB will need continued EU funding to enable the preparation of a TDR

In its Strategy Session in 2013 the CERN Strategy Council stated as part of its 'European Strategy for Particle Physics' that there is "*a strong scientific case for a long baseline neutrino program exploring CP violation and the mass hierarchy in the neutrino sector*". The Council recommended that "*CERN should develop a neutrino program to pave the way for a substantial European role in future long-baseline experiments*", which CERN has since then in part done with the development of the CERN Neutrino Platform. This Platform has predominantly been used to support the US DUNE Liquid Argon detector project and to some extent the T2K and Hyper-Kamiokande near detector projects. The Council also recommended that "*Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan*".

After this recommendation was made in 2013 the construction of the ESS began in 2014 and a Design Study of the use of the ESS linac to create a uniquely intense neutrino beam enabling measurements at the second oscillation maximum started. In view of the outstanding opportunity for precision neutrino experimentation offered by this use of the ESS linac, the European COST Association provided ca 0.3 MEUR to be used for networking for this project as from 2016 and the EU H2020 program provided 3 MEUR for the financing of the Design Study as from 2018. This has enabled a vigorous start to the study of the specific possibilities for a world-leading and complementary long-baseline neutrino project.

In order to demonstrate in the form of a Technical Design Report the feasibility and performance of ESSνSB as a precision experiment, having in the longer-term perspective a very significant muon-physics potential, the ESSνSB consortium will need continued support from EU as from 2022 in the form of Preparatory Phase funding. In view of this, we proposed that the CERN Strategy Council should include in its upcoming 'European Strategy for Particle Physics', the opportunity, new since 2013, of the ESSνSB Collaboration producing a thorough Technical Design Study of the proposal to use the European Spallation Source linac to drive a uniquely intense Long Baseline neutrino beam.

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[7] http://essnusb.eu/

Participating countries in EuroNuNet (COST Action 15139, http://euronunet.in2p3.fr/):

1) Bulgaria
2) Croatia
3) France (**Coordinator**)
4) Germany
5) Greece
6) Italy
7) Norway
8) Poland
9) Spain
10) Sweden
11) Switzerland
12) Turkey
13) United Kingdom
14) Observers:
    a) Institute of High Energy Physics, Beijing
    b) CERN - European Organisation for Nuclear Research
    c) ESS – European Spallation Source ERIC

Participating institutions in ESSnuSB Design Study (H2020 Grant-777419, http://essnusb.eu/):

1. Centre National de la Recherche Scientifique (**Coordinator**, IPHC and IPNO)
2. Uppsala University (WP3 coordination)
3. KTH Royal Institute of Technology
4. European Spallation Source ERIC (WP2 coordination)
5. Cukurova University, Adana
6. Universidad Autonoma de Madrid (WP6 coordination)
7. NCSR 'Demokritos', Athens
8. Istituto Nazionale di Fisica Nucleare (Milano, Padova)
9. Rudjer Boskovic Institute
10. Sofia University St. Kliment Ohridski (WP5 coordination)
11. Lund University
12. AGH University of Science and Technology, Krakow (WP4 coordination)
13. European Organisation for Nuclear Research
14. University of Geneva
15. University of Durham