Opportunities in Accelerator-based Neutrino Physics in Japan

Input Document to the European Particle Physics Strategy

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ABSTRACT

This document provides the inputs to the ongoing European Particle Physics Strategy based on the opportunities offered by the accelerator-based neutrino programme in Japan to which the 2013 European Strategy recommended due to the "*Rapid progress in neutrino oscillation physics, with significant European involvement"*, "*CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments"*, that led to the establishment of the CERN neutrino platform and that "*Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan"*, that supported the expansion of the already substantial European presence in the Japanese long baseline neutrino programme to encompass Hyper-Kamiokande in addition to T2K.

There have been significant developments since the publication of the European Particle Physics Strategy with the establishment of the Hyper-K collaboration, whose far detector will start to be constructed in 2020, and the prospect of the T2K running beyond 2021, with increasing beam power due to an upgrade of the J-PARC Main Ring accelerator, up to the start of data taking for Hyper-K, thus assuring a continuous period of data taking in Japan in the next decades. There is significant European participation in both experiments and an already ongoing engagement from CERN through the Neutrino Platform and the registered-experiment status of T2K.

Recommendations to the European Particle Physics strategy are presented on the accelerator-based neutrino programme of those facilities, based upon the foundations of the current and past work and future opportunities offered by the accelerator neutrino programme in Japan.

STRATEGIC CASE

Tokai-to-Kamioka (T2K)[i] and Hyper-Kamiokande[ii] (Hyper-K) are world-leading neutrino experiments that are/will be able to address major open questions in neutrinos physics oscillations. Furthermore, Hyper-K will improve on Super-Kamiokande's[iii] (Super-K) world-leading sensitivities for proton decay and astrophysical neutrinos such as supernova or relic neutrinos. The answers these experiments provide to the open questions in neutrino physics will indicate future directions in the science both for the development of new experiments and the refinements of theoretical models. A recent successful example was, for instance, the observation of the electron neutrino appearance in T2K[iv] that drove the direction of future neutrino experiments as well as the theory motivating the search for *CP* violation.

T2K is a currently operating long baseline experiment hosted jointly by KEK/J-PARC (Japan Proton Accelerator Research Complex) in Tokai, Japan, and Super-K near Toyama, Japan. A second phase of the experiment is envisaged (for clarity we will call this phase T2K-II) after around 2021 that will be characterised by an increase of the beam power up to 1.3MW around 2025 and an upgraded near detector facility. The Hyper-K experiment builds upon the infrastructure and experience of, and will significantly extend upon the reach of, the T2K experiment. Current indications from T2K of a maximal value of *CP* violation may allow Hyper-K to have a large impact after a few years of data taking.

As Europe has a strong presence in the leadership of the experiments, it will play an important role in any major breakthrough in the next decades and consequentially will influence the international directions in physics. European countries and CERN will directly influence the neutrino physics program to ensure European expertise plays a prominent role in future experiments.

European countries are leading pioneering work on the critical challenges of the experiments spanning the three main areas of:

- Beam upgrades from the current beam power to the beam power needed for T2K-II and Hyper-K via a staged approach;
- Near detectors, both upgrades to existing and entirely new detectors, to reduce the systematic errors on the oscillation analysis but also to provide a short baseline configuration for sterile neutrino studies;
- Far detector: contributions to the construction of the Hyper-K detector.

Furthermore, to fully achieve the future potential of the experiments, we are contributing to ancillary experiments such as NA61/SHINE[v] at CERN for measurements of hadron production from the interaction of the beam with the target, thus providing a reduction of the beam flux systematic errors at T2K and Hyper-K.

In the following, we first present the scientific case, in which we will expand on the above topics, and then for each area we will provide a more detailed description of our work and write our recommendations to CERN and input to the European Particle Physics strategy.

SCIENTIFIC CASE

Neutrino oscillations from one type (or flavour) into another have been extensively studied since their discovery at the end of the 20th century. Experiments have detected fewer neutrinos of a given flavor than those produced (disappearance), or have observed more neutrinos of a different flavor than those produced (appearance) in line with the predictions of the oscillation model. However, the model also describes whether neutrinos or antineutrinos have the same behaviour or not (*CP* violation). The *CP* violation parameters are extremely important to measure as *CP* violation in the neutrino sector is considered to be an important component of the model describing the matter-antimatter asymmetry in the Universe. Furthermore, whilst neutrino oscillations imply the neutrino has mass, the exact ordering of the neutrino masses (mass hierarchy) is unclear. This measurement is also extremely important as many models seeking to unify the forces of nature predict a particular ordering. Measuring these *CP* violation and mixing parameters is extremely challenging and requires detectors of greater precision than ever before and will need both a precise understanding of the systematic uncertainties, and much larger datasets.

The T2K experiment in Japan is a long baseline neutrino experiment with a 295km baseline using the ν_μ (anti- ν_μ) beam produced by the J-PARC accelerator on the East coast of Japan. The beam is measured first at the near detector suite 280m away from the neutrino beam target, and then again, after it has crossed the country to the opposite coast of Japan, by the Super-K detector after flavour oscillations occur. The initial goal of the T2K experiment was the observation of electron neutrino appearance from the muon neutrino beam. This was achieved within a few years from the start of data taking[vi], resulting in Koichiro Nishikawa sharing the 2016 Breakthrough Prize for Fundamental Physics, along with K2K and T2K collaboration members. Using this discovery as a tool for future discovery, T2K is now focussing on the search for *CP* violation, and has already published evidence at 2σ that δ_{CP} is not conserved in neutrino mixing[vii].

The T2K Collaboration has also submitted a proposal for an extension of T2K running (this phase of the experiment is called T2K-II) accumulating 20×10^{21} protons-on-target, that is 6 times the present exposure, which has received stage-I approval at J-PARC. This aims at initial observation of *CP* violation at the 3σ level or higher significance if the *CP* violation is maximal, as currently favoured by the T2K results, as well as precision measurements of the atmospheric mixing parameters. While the present configuration of ND280 leads to systematic errors of the order of 6%, the goal is to bring this number down to ~ 4% for T2K-II.

Super-K, which acts as the T2K far detector, but also has its own non-accelerator physics programme, will be the first large-scale water Cherenkov detector to load with gadolinium for enhanced neutron detection capability. The primary physics goal is the first observation of relic supernova neutrinos, but the high neutron detection efficiency will also enhance the T2K CP violation search.

The goal of the Hyper-K experiment is to achieve for the first time observations and measurements within its very rich physics portfolio that spans from *CP* violation in the leptonic sector and neutrino mixing parameters to proton decay, atmospheric neutrinos and neutrinos of an astronomical origin. The Hyper-K experiment builds on the successful strategies used to study neutrino oscillations in the Super-K, K2K and T2K experiments, with improvements designed to study the *CP*-violation (δ_{CP}) and mixing parameters. Larger detectors with improved photosensors will be used to increase statistics: the Hyper-K detector will increase the far detector fiducial mass from ~29ktons to 187ktons with one tank and two-fold with two tanks. The baseline design includes two 60m high, 74m diameter cylindrical detectors each corresponding to a fiducial mass of 187ktons. The two detectors will be built in a staged approach and in different locations, starting with the detector in Japan at a baseline of 295km. There are ongoing studies for a second detector in Korea[viii] at a baseline of about 1000km.

For the accelerator neutrino beam program, higher available beam power will increase statistics even further. Thus, the control of the systematic uncertainties needs to be improved to ~ 3% or below for Hyper-K's physics goals. This will be achieved by the construction of an additional intermediate water Cherenkov detector (IWCD), and by possible further ND280 upgrades. The addition of IWCD will expand the physics portfolio of the experiment through enlarging the parameter space for short-baseline neutrino oscillation studies and providing cross sections for atmospheric neutrino studies.

For the electron (anti)neutrino appearance samples, neutrino and anti-neutrino beams at higher beam power will be used allowing exclusion of *CP* conservation in neutrino oscillations at 5σ significance for most of the allowed phase-space at higher precision.

Atmospheric neutrinos are sensitive to the mass hierarchy, and will allow Hyper-K to determine the mass hierarchy with 3σ significance for the available phase space regardless of the hierarchy.

Furthermore, the combined analysis approach is also useful for the violation of *CP* symmetry search: although most of the sensitivity to δ_{CP} comes from beam neutrinos, there can be degeneracy between the mass hierarchy and the value of δ_{CP} for certain combinations of true values of the two. In these cases, the atmospheric neutrinos allow breaking the degeneracy and increase the ability to reject the conservation of *CP* symmetry.

With its huge target mass, superior sensitivity to proton decay and astrophysical neutrinos, i.e. solar neutrinos, supernova burst neutrinos and supernova relic neutrinos, is expected. One of the major motivations of solar neutrino research is testing the solar model predictions as well as the study of neutrino properties themselves. With Hyper-K, the day-night asymmetry can be measured with high precision. The result will significantly improve the current KamLAND best value above 3.5σ within 10 years. Moreover, many precise measurements of the solar neutrino would also be possible, e.g. the undiscovered hep process neutrino, the shape of the solar neutrino energy spectrum where the beyond standard model physics could be, and the seasonal variation of the flux.

A second detector in Korea will enhance sensitivities to non-standard interactions of neutrinos and mass ordering determination using the beam by virtue of the large matter effects.

The Hyper-K experiment will use much of the existing infrastructure used by the currently running T2K experiment, particularly the beam line and near detectors. Hyper-K will also benefit from an improved T2K data analysis techniques. Several important T2K upgrades and improvements are planned for the coming years, and these will have a direct impact on the improved Hyper-K performance. Hyper-K will also benefit from the expertise and experience gained through implementing these upgrades. Furthermore, these upgrades will serve as a testbed for new near detector designs proposed for Hyper-K.

The Super-K experience with Gd-loading will be useful for any future loading of gadolinium into other Water Cherenkov detectors. Future water Cherenkov detector will also benefit from the extensive research done by Super-K to optimize the water purification system, as well as material compatibility tests.

In order to take full advantage of the available statistics in the far detectors, the near detectors of T2K and Hyper-K should be optimally developed and used to lower the systematic errors through a direct measurement of the the unoscillated neutrino spectrum. Quantitative requirements have been identified by the Hyper-K Near Detector Working Group for the near detector suite for Hyper-K and are described in the CDR[ix]. Based on these requirements, a near detector suite with a baseline of the following three detectors is required:

- an on-axis detector that will measure the beam direction with sufficient precision and monitor the neutrino event rate;
- an off-axis magnetized tracking detector that will separate the wrong-sign and right-sign components of the beam and be used to study the recoil hadron system;
- an intermediate water Cherenkov detector with off-axis spanning and Gd loading capabilities that will measure the intrinsic ν_e(anti-ν_e) components of the beam and the $\sigma_{\nu e}/\sigma_{\nu\mu}$ and $\sigma_{\text{anti-}\nu e}/\sigma_{\text{anti-}\nu\mu}$ cross section ratios, the neutrino energy vs. final state dependence and neutron multiplicities.

In the case of the on-axis detector, it is expected that the INGRID detector, already part of the T2K suite of detectors at 280m, with minor upgrade will be sufficient. The off-axis magnetised detector is expected to be based on an upgrade of the T2K ND280 detector. T2K is carrying out an upgrade of ND280 for the T2K program, but it is expected that additional upgrades to the detector and infrastructure will be necessary for Hyper-K. The intermediate detector is a new detector that requires a new facility outside of the J-PARC site.

The current ongoing and planned work for the ND280 upgrade for Hyper-K and the IWCD are described in the next sections.

BEAM UPGRADE

The accelerator and beamline have been successfully operated up to 485kW beam power during T2K operations up to now. The planned operating power increases are to 800 kW or higher for T2K-II and up to 1.3MW in the Hyper-K era, which will be achieved by increasing the repetition rate of the beam and increasing the number of protons per pulse. The J-PARC accelerator complex (primary beamline, target hall, and secondary beamline) will be upgraded from the existing accelerators and beamlines that have been operated for the T2K experiment up to a power of 485kW in 2021 to deliver 800kW or higher power. The calculated neutrino flux produced by the beamline is a primary input to neutrino oscillation analyses in the T2K and Hyper-K experiments. Consistent with the T2K model, the upgrade and operation of the accelerator complex will be the responsibility of KEK and J-PARC. The upgrade and operation of the primary beamline and target hall and secondary beamline up to 1.3MW, led by the KEK neutrino group, will be the responsibility of the Hyper-K collaboration. The neutrino flux is calculated using inputs from proton beam current, position and profile monitors, horn current and field measurements, beamline geometry and alignment information, and external measurements of hadron interactions on material and at energies relevant for T2K/Hyper-K.

Neutrinos are delivered to the neutrino beamline by the J-PARC accelerator complex, directly from the 30GeV Main Ring. The upgrade of the Main Ring to its nominal power of 750kW, and beyond, will be achieved by an upgrade of the Main Ring RF and the magnet power supplies, which will allow the repetition rate to be doubled. Based on high intensity studies of the current accelerator performance, it is expected that 1-1.3MW beam power can be achieved after these upgrades. The delivered proton beam strikes a neutrino production target to produce secondary particles, mainly pions and kaons, which are focused along the beam-line by magnetic horns and decay in flight into muon neutrinos and muons in a 94m long decay volume. The purpose of the secondary beamline is to produce an intense, narrow band neutrino beams with the so-called off-axis method[x]. In this method the neutrino beam is purposely directed at an angle with respect to the baseline connecting the proton target and the far detector, Super-K. The off-axis angle is set at 2.5° so that the narrow-band muon neutrino beam generated toward the far detector has a peak energy at ~0.6GeV, which maximizes the effect of the neutrino oscillation at 295km and minimizes the background to electron neutrino appearance detection.

Discussions between the CERN beam division and T2K/Hyper-K have started for possible contributions to the beam upgrade. Furthermore, crucial work for the upgrade within the RaDIATE (Radiation Damage In Accelerator Target Environments) Collaboration is ongoing since its establishment (CERN and European institutes are among the founding members) to better understand and predict the radiation response of structural window and target materials. This work is needed in order to design and use material that can withstand the beam power up to 1.3MW. Several tests have already been performed at PNNL (US) and Culham (UK). An irradiation facility at the CERN beam dump would be optimal to support the beam work that, due to the highest beam power, presents new challenges from the irradiation point of view and new tests for the target and material are needed. This will be beneficial not just for CERN and the European institutes working on the neutrino beam, but for all similar needs by other beamlines.

Recommendation

CERN has world-leading expertise in beam design and operation and its support of beam development for long baseline neutrino experiments is essential. This engagement will enable the pursuit of high intensity neutrino beams to be achieved. The idea of an irradiation facility at CERN should be pursued. It will help in the study of the irradiation material in Europe. Supporting the work of the European institutes using a European facility, it will be important for the long baseline experiments of which European institutes are members and, finally, it can be relevant for other similar issues for other beams.

ND280 UPGRADE

The upgrade of the T2K Near Detector ND280 is needed in order to reach a systematic uncertainty at the 4% level, matching the needs of the T2K-II phase. This phase of the T2K experiment can provide a 3σ exclusion of *CP* conservation for 36% of the δ_{CP} phase space, if the neutrino mass ordering is known.

The Upgrade of the T2K Near Detector ND280 was launched by T2K in 2016 and submitted to CERN SPSC an EOI (SPSC-EOI-15, 2017)[xi] (The HPTPC beam test (NP-03) originated from this EOI.) and a proposal (SPSC-P-357, 2018)[xii]. A TDR has now been written and was submitted to SPSC in December 2018. The project has a strong and vibrant participation of European laboratories (Spain, France, Italy, Switzerland, Germany, Poland, Russia, CERN).

The detector design significantly improves the performance provided by the current ND280 detector. In particular we achieve full polar angle coverage for the muons produced in Charged Current events, improve the tracking efficiency of pions and protons stopping inside the scintillator detector and improve the separation of electrons from converted gammas required for electron neutrino studies. The downstream part of the current ND280 detector is not altered and will continue to provide useful information on the neutrino flux and cross-sections, as well as a comparison point with respect to pre-T2K-II data.

These state-of-the-art detectors will also greatly increase the physics capabilities of the Near Detector complex (electron/gamma separation, particle identification, neutron detection capabilities) beyond T2K, in particular providing new information to constrain the neutrino-nucleus interaction model. It will therefore be an asset also for the Hyper-K experiment.

The new detectors have all been designed in Europe and include:

- a highly segmented scintillator detector, the Super-Fine-Grained Detector (SuperFGD), built with 1cm per side scintillator cubes read out by three WLS fibers along orthogonal directions. The Super-FGD is an innovative device with excellent detector performance. We have observed in the first tests that in realistic conditions a MIP crossing a single cube will produce more than 30 photoelectrons per WLS fiber. The timing resolution per fiber is better than 1ns. With this precise information we will be able to track over 4π solid angle pions and protons stopping in this detector. Moreover, its high granularity will allow to distinguish electrons produced by electron neutrino interactions from converted photons. Studies are ongoing to evaluate the potential to detect neutrons in this detector.
- two resistive Micromegas TPCs. The TPC will measure charge, momentum, track angles and dE/dx with excellent efficiencies and low systematics. Preliminary measurement in the test beam show that the space point resolution is at the 300μm level, to be compared to 600μm for the existing TPC in ND280.
- six Time-of-Flight (TOF) detectors. The TOF, consisting of cast plastic scintillator readout by MPPC, will reach a time resolution of 150ps.

Prototypes of these detectors have been tested in Summer 2018 at the CERN PS T9 and T10 beam lines, validating the technology choices and obtaining an excellent performance. The construction of these detectors will provide new high-quality neutrino beam interaction data useful to constrain the cross section models. We have checked the effectiveness of the new detectors with detailed simulations. Propagating the new information by the upgraded ND280 all the way to the prediction at the T2K Far Detector, we obtain a significant improvement both with respect to a fixed neutrino interaction model, and with respect to the capability to discriminate between different models. On average, the post-fit uncertainty after taking into account the data provided by the upgraded detector will be 30% lower than before. Furthermore, the uncertainties on the near to far extrapolation due to model dependence will be reduced substantially. The upgraded ND280 detector construction will be performed in 2019-2020 aiming to install it in Japan in 2021. The new components of the upgraded ND280 detector will be built to a large extent in Europe.

The proposal foresees a participation of CERN in this project, subject to approval of CERN SPSC and CERN management, with contributions in these areas:

- the TPC gas system;
- the production of the resistive Micromegas;
- the mechanics and the calibration system of the SuperFGD.

The upgraded ND280 detector will be running during the T2K-II data taking.

The Hyper-K experiment will use the same near detector site, but currently an assessment of the further upgrade of the ND280 detector is being addressed. The work in collaboration with CERN will be crucial in developing and testing new technologies to go beyond the capabilities of the current upgraded ND280.

Recommendations

It is important for CERN to continue to support the effort in the ND280 detector that it has supported since the beginning with the donation of the UA1 magnet used by ND280 since its design, and the ND280 TPC development, testing and construction.

The use of the CERN Neutrino Platform as well as the contributions to the three items listed in the above section (TPC gas system, production of resistive Micromegas and mechanics and the calibration system of the SuperFGD) are crucial and will support the European effort on the neutrino physics that is part of the role that CERN has in Europe to support its community.

Furthermore, planning towards Hyper-K, Europe is engaging in addressing future developments of the ND280 upgraded detector and the expertise and support from CERN will be invaluable.

Europe is leading the ND280 detector, it is crucial for CERN to support this effort.

INTERMEDIATE WATER CHERENKOV DETECTOR (IWCD)

A new complementary near detector to ND280 is being planned for the Hyper-K experiment. It is a Water Cherenkov detector similar to the far detector, and different from ND280 which is a tracking detector. Due to the further distance from the beam target than ND280, i.e. 1-2km, it is called the “intermediate” Water Cherenkov detector (IWCD).

The detector provides an identical nuclear target to the Hyper-K far detector with no need for subtraction analyses. It also naturally provides a 4π angular coverage. The detector size is large enough to contain neutrons, and with gadolinium loading, the detector would be able to study the neutron multiplicities in neutrino and antineutrino interactions with different observed final states. The IWCD can measure electron (anti)neutrino rates due to the large active shielding region that can be used to reject sources of external backgrounds.

These electron (anti)neutrino candidates can be used to measure the intrinsic ν_e(anti-ν_e) components of the beam and the $\sigma_{\nu e}/\sigma_{\nu\mu}$ and $\sigma_{\text{anti-}\nu e}/\sigma_{\text{anti-}\nu\mu}$ cross section ratios. The design for the IWCD includes the capability to make measurements at different off-axis angles by moving the instrumented detector vertically. This capability will allow the detector to probe the relationship between neutrino energy and final state particle multiplicities and kinematics.

European countries have been pioneering and involved in this project since the beginning contributing to its design and development.

There is potential to test many aspects of the IWCD design, and prove our ability to calibrate it, with a smaller proto-type detector deployed in a test-beam. It is crucial to test the method as new PMTs, the multi-PMTs, whose design is an evolution of the KM3NET domes, are used for the first time in this kind of detector and uncertainties in measurements in a near detector will impact the accuracy of the results they produce. Furthermore, in addition to the calibration effort, the prototype can have physics impact through the study of charged pions, whose results can affect *CP* violation studies.

Potential beam opportunities at CERN and design of the test module are under investigation at this time.

Recommendations

The high precision needed by the new Japanese long baseline experiment Hyper-K will require addressing new challenges for which a suite of near detectors is needed. The IWCD will complement ND280 and will require its own test beam and development to test its new technology.

The CERN platform should engage with the IWCD test beam and support this new technology. Testing of the mPMTs will also be relevant for the Hyper-K far detector and the possibility to adopt a hybrid photosensor coverage (20” PMTs and mPMTs) for the its inner detector.

FAR DETECTOR HYPER-KAMIOKANDE

The Hyper-K far detector will constitute the largest underground detector in the world and will face several technology challenges related to its size. They are both related to the propagation of the light in the water, the light collection with PMTs and the pressure they can withstand, the cabling and network system, the electronics, DAQ and calibration. Also, although the Water Cherenkov technology is the same as Super-K, its large size presents new challenges. These technology challenges are currently being addressed in its design. We are seeking to benefit from the CERN expertise in the engineering support of mechanical structures and electrical design of the various components under high pressure environments that we would be able to develop and test within the CERN neutrino platform.

Recommendations

CERN's contribution to the effort to develop long baseline neutrino experiments and provide a balanced support to the activities are essential. Involvement in the design of the Hyper-K far detector can be provided based on CERN expertise that will involve the usage of the CERN neutrino platform including in particular support for electronics development.

ANCILLARY EXPERIMENTS

Ancillary measurements are indispensable to achieve the required precision required by long baseline neutrino experiments in both beam and cross-section predictions, which both rely on details of hadron scattering processes that are difficult to model. Neutrino beam flux predictions are thus tuned to external hadron production data, and neutrino-nucleus interaction models incorporate hadron-nucleus scattering measurements.

NA61/SHINE

The NA61/SHINE experiment at CERN has already been very successful at measuring the yields of secondary hadrons generated by 31GeV/c protons on carbon targets for the T2K experiment[xiii], which are considered indispensable to reach the requested precision of the experiment. The NA61/SHINE hadron production measurements reduced the T2K hadron production uncertainty from > 20% to around 5%. However, there are still limiting factors in the measurements provided for T2K that can be addressed by performing additional measurements in the NA61/SHINE experiment for T2K. Furthermore, higher precision, higher beam power, and a new target design present new needs for T2K-II and especially the Hyper-K experiment. Continued work by the N61/SHINE collaboration engaging with the new needs by the long baseline experiments and providing the needed data is crucial. In particular Hyper-K will use a different target from T2K that would need to be tested. The ability to also provide additional information to what is currently provided for T2K would be needed for improving the precision of the experiment.

Recommendations

The NA61/SHINE experiment has provided excellent and essential input to long-baseline neutrino experiments and CERN's continued support of this experiment is a key ingredient in reducing the systematic uncertainties of the long baseline neutrino oscillation experiments related to the beam production decreasing the uncertainty related to the hadron production from the interaction of the proton beam with the target and surrounding material.

Hadron scattering experiments

Each of the widely-used neutrino generator MCs uses a semi-classical cascade model to simulate final state interactions, which rely on hadron-nucleus scattering cross sections as input—but in many cases there are no data available to anchor these models. In particular, measurements in the 1GeV region and below are needed, because this is where the hadronic modelling issues pile up and lead to uncertainties in neutrino oscillation measurements. The most significant needs are for proton, neutron, and kaon scattering measurements on nuclei, although an expansion of existing pion-nucleus measurements and correlations between proton-nucleus and pion-nucleus measurements would enable further precision in neutrino-nucleus interaction modelling. These measurements are needed to achieve the T2K/Hyper-K goals of reducing neutrino-nucleus interactions uncertainties to 2-3%.

CERN has already supported such measurements through the 2018 beam test in T10 made by the HPTPC Collaboration (NP-03). The ongoing survey of interest in a low momentum beamline at the Neutrino Platform is a very attractive prospect for addressing this type of systematic error.

Recommendations

The CERN test beam facilities are crucial platforms for hadronic scattering measurements, which constitute a significant source of uncertainty in neutrino oscillation experiments. A low momentum beamline at the Neutrino Platform would contribute substantially to the T2K and Hyper-K physics goals, as well as to the wider global neutrino physics community.

CONNECTIONS WITH THEORY COMMUNITY

Neutrino-nucleus interaction physics is a crucial area of study with active fields in both experimental and theory communities. Since the last European Strategy exercise, the NuSTEC collaboration between theorists and experimentalists was formed. This is a crucial activity that is already yielding positive results for neutrino interaction modelling, but further engagement with the nuclear theory communities is needed.

Recommendations

T2K relies strongly on the modelling of neutrino scattering, a field that is dominated by European groups. CERN should facilitate further engagement between the nuclear and particle theory communities to make progress on this important source of systematic uncertainty in neutrino oscillation experiments.

SOCIETAL AND ECONOMIC IMPACT

Members of the T2K, T2K-II and Hyper-K experiments are engaged in knowledge exchange through presentations and dissemination of the work performed through public outreach activities. Furthermore, secondments and placements with the European industries, especially for Hyper-K are ongoing or being planned. Web pages and social media are regularly updating informing of the status of the experiments and latest results.

Furthermore, the experiments provide student training for STEM (Science Technology, Engineering and Mathematics). This highly trained workforce will be able to pursue a future career in particle physics and in a wide variety of other fields including finance, industry, communication, computing and teaching. The experiments are already supporting students for PhD, Masters, Erasmus+, undergraduate projects and summer studentships. Many students have already graduated, and obtained skills they would not have been able otherwise to get.

Supporting the work in the long baseline neutrino programme in Japan will provide skilled workforce, engagement of the PhD students with the CERN platform, stronger collaboration with CERN of the involved countries and industrial impact collaborating with the European industries.

SUMMARY

Neutrino oscillation physics through long baseline neutrino experiments has a big challenge ahead that is the observation of the *CP* phase as well constraining the other oscillation parameters. CERN has strongly supported T2K through the ND280 work since the beginning of the experiment and continues to be supportive now with the test beam at the CERN Neutrino Platform.

CERN is uniquely placed to continue its involvement in ND280 and provide support for the beam, IWCD and the Hyper-K detectors. These detectors are all strongly supported by the European countries from the design to the construction and operation. Supporting this effort will reinforce CERN both as centre of the European activities as well as providing vital help to the work of the European countries and development of the detectors.

Also, supporting ancillary facilities as NA61/SHINE as well as test beam facilities is considered indispensable to the reduction of the experimental uncertainties and reach the full potential of the experiments.

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