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Neutrinos@CERN: A Community-Driven Contribution to the Update of the European Strategy for Particle Physics

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The Neutrinos@CERN workshop was held on January 23-24, 2025, at CERN. Organized by the CERN Neutrino Platform and Physics Beyond Colliders, this two-day event aimed to explore opportunities for neutrino physics experiments at CERN, leveraging existing, planned, and proposed facilities. The workshop brought together a significant portion of the neutrino physics community to discuss these possibilities and provide input to the European Strategy for Particle Physics Update (ESPPU). This document summarizes these inputs and the corresponding community statements.

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1 Introduction

The **Neutrinos@CERN** workshop took place at CERN on January 23–24, 2025, gathering a significant fraction of the European accelerator neutrino community. The roughly 300 participants are involved in key neutrino experiments and related measurements. In addition to CERN-based experiments, the majority of European neutrino physicists contribute to the two flagship projects in the field of accelerator oscillation physics: the DUNE experiment in the US and the Hyper-Kamiokande experiment in Japan. CERN's contributions are broad and essential for the successful outcome of these projects.

Experimental studies of neutrino masses and mixing have the potential to revolutionize our understanding of particle physics. Neutrino masses are the only sure indication of a new physics mass scale and constitute the first-order beyond-standard model (BSM) term of the Lagrangian in the most general and model-agnostic Effective Field Theory. Neutrino mixing further provides a powerful probe of flavor symmetries that complements measurements in the quark sector. Moreover, the size of neutrino masses and any neutrino/antineutrino asymmetry are pivotal in cosmological models. Addressing all of this, next-generation accelerator-based neutrino oscillation experiments provide one of today's most compelling programs to search for BSM physics, including Dark Matter, and with major impact on the Standard Model, towards a unification of the fundamental interactions. This program includes searches for deviations from the standard PMNS oscillation paradigm and searches at near detectors in a beam-dump-like setup. Beyond their BSM reach, a unique aspect of these experiments in the present particle physics landscape is the presence of a sure and high-profile physics return in about the next 10 years: the characterization of charge-parity (CP) violation in the lepton section (potentially linked to the matter-antimatter imbalance in the Universe), the determination of the neutrino mass ordering, the precise measurements of neutrino mixing. As mandated by the 2020 update to the European Strategy for Particle Physics, CERN's existing and planned contributions are broad and essential for the successful realization of these projects' far-reaching physics goals. A strong neutrino program at CERN is an essential part for enabling decisive European participation in international projects that provide a strong and distinct path to major physics breakthroughs in a relatively short term, in addition to compelling access to BSM physics.

CERN serves as the technology hub for the development of detectors for current and future neutrino experiments through the CERN Neutrino Platform, which already has delivered major advancements in the field over the past decade. Among its most significant contributions is its partnership with Fermilab to introduce the membrane cryostat to our field, a breakthrough that made the construction of DUNE technically feasible at the multi-kiloton scale. This innovation was complemented by the development of two DUNE demonstrators, NP04/ProtoDUNE-HD and NP02/ProtoDUNE-VD, which have played a pivotal role in validating key technologies for the experiment. The Neutrino Platform also oversaw the comprehensive overhaul of NP01/ICARUS, now successfully operating at Fermilab within the short-baseline neutrino (SBN) program. Owing to the unique expertise in detector technologies, availability of engineering resources and infrastructures for both detector validation and commissioning, CERN was instrumental to the realization of T2K's upgrade of ND280, the magnetized near detector, to enable high-precision measurements of the neutrino-nucleus cross section with novel neutrino detector technologies. ND280 will continue its operation during the Hyper-Kamiokande era. One of the last approved Neutrino Platform projects is NP08, which will enable the Hyper-Kamiokande collaboration to deliver the underwater bias and front-end electronics units for the photomultipliers of the water-Cherenkov far detector. With NP08, CERN centralizes the European efforts in Hyper-Kamiokande by providing support to the activities aimed at assembling, testing, calibrating and shipping all the 900 units to Japan.

Beyond DUNE and Hyper-Kamiokande, the Neutrino Platform has contributed to devising monitored neutrino beams (NP06/ENUBET), enhanced the near-detector complex of T2K (NP07/ND280 and NP05/BabyMind), and supported the LHC neutrino detectors FASER and SND@LHC prior to their installation.

CERN provides key support to the global neutrino oscillation physics program, leveraging its extensive infrastructure. A prime example is the NA61/SHINE experiment, which employs a large-acceptance spectrometer to deliver the most precise hadroproduction measurements relevant to T2K, NOvA, DUNE, and Hyper-Kamiokande, using both thin and replica targets corresponding to these neutrino beams. This has led to an impactful improvement of the uncertainties of neutrino fluxes.

Currently, CERN does not provide users with a neutrino beam in the energy range of interest for oscillation studies. Consequently, the contributions mentioned above are utilized in Japan and the US on long-baseline Superbeams—T2K and NOvA at present, and Hyper-Kamiokande and DUNE in the forthcoming years—as well as on the short-baseline neutrino program in the US. On the other hand, CERN provides major contributions to the analysis program of a wide range of neutrino experiments, through both EP-NU and theory groups. In addition, CERN performs first-class neutrino physics at higher energies. The first observation of neutrinos—with TeV energies—from the LHC by the FASER and SND@LHC experiments testifies to this. Similarly, the approval of the Beam Dump Facility (BDF) and the SHiP/NA67 experiment further enhances these opportunities. SHiP/NA67, which has been designed to explore a wide class of BSM models related to the dark sector and Heavy Neutral Leptons, also offers a testbed for specific BSM models explaining neutrino oscillations, and—as a by-product—an unprecedented source of multi-GeV neutrinos. This will be exploited to advance our knowledge of ν_τ cross sections, high-energy ν_e scattering, and charm production.

It comes as no surprise that physicists working in the high-energy regime of neutrino cross section measurements have benefited from the unique opportunities offered by the LHC and are now proposing a second generation of experiments to capitalize on the potential of the High-Luminosity LHC. These proposals were also discussed at Neutrinos@CERN.

Last but not least, the role of Physics Beyond Colliders (PBC) at CERN is to be underlined not only because PBC has been instrumental to driving many of the above activities, e.g., the BDF, SHiP/NA67, or FASER, but also for its continuing support of related activities. And while the workshop and this input to the ESPPU is centered around activities at CERN, it is worthwhile to point out the breadth of leading contributions within the European community to neutrino physics in general, e.g., ICECUBE, JUNO, or KM3NeT/Orca.

2 Input to the ESPPU

Beyond showcasing current initiatives and proposed activities in neutrino physics at CERN, this workshop provided a unique opportunity to discuss strategies for strengthening CERN's role in the field in the coming years. It also aimed to offer guidance for the European Strategy for Particle Physics Update (ESPPU). During the workshop's discussion forum, as well as in the weeks that followed, we gathered valuable input from participants, including insights from the Spokespersons and leading representatives of the key neutrino experiments mentioned earlier. This collaborative effort allowed us to consolidate a common vision for CERN's future in neutrino physics.

Our conclusions are encapsulated in six community statements, which we would like to present to the ESPPU's Physics Preparatory Group ahead of the Venice Open Symposium and the final deliberations scheduled for 2026. Despite the diversity of neutrino programs at CERN, we believe that these statements reflect the shared views of the community and offer a concrete contribution to shaping and implementing the Strategy in our field.

2.1 The CERN Neutrino Platform

The establishment of the CERN Neutrino Platform, which was recommended in the 2013 Update of the European Strategy for Particle Physics, aimed at fostering advances in accelerator neutrino science and anchoring CERN's support for the new generation of long-baseline experiments in Japan and the US, has been a tremendous success, which is a direct result of the mandate provided by the previous ESPP updates. The Neutrino Platform enables coherent development and demonstration of future technologies, thanks to its facilities and the CERN wide offer of test beams, including two dedicated Very Low Energy beamline in the North Area, and essential beamline facilities in the East Area for detector R&D. The CERN Neutrino Platform has positioned European groups at the forefront of the field, securing leading roles that would have been inconceivable without this infrastructure. We believe that the aims and objectives of the Neutrino Platform remain essential for sustaining European contributions to the field, even in the Hyper-Kamiokande and DUNE era. Ensuring proper **recognition and financial support for the Neutrino Platform** in this context **should be considered a top priority for the ESPPU** in the neutrino sector.

2.2 The CERN Neutrino Physics Center

Over the past five years, the EP-NU group grew substantially, enabling CERN and users to significantly contribute to current and future long-baseline experiments. EP-NU also created strong inter-institutional links whilst working on neutrino-nucleus cross sections. These contributions have benefited from strong yet informal coordination with the CERN Theory Group, addressing key topics such as neutrino cross sections, phenomenological predictions in BSM frameworks, and the interplay between neutrino and nuclear physics. In particular, the EP-NU group is strongly contributing to modeling neutrino interactions targeting precise and accurate neutrino oscillation measurements. These developments will be crucial, in particular for DUNE because it will exploit a large energy band beam and will rely on Argon nuclei for which nuclear effects are important and complex. However, this less coordinated approach has been pursued largely on a voluntary basis, following a bottom-up model where resources were secured to address specific tasks, often in response to the immediate needs of experiments. While effective in the short term, this model has shown limitations over time, particularly when compared to more structured initiatives such as the LHC Physics Center at Fermilab. The absence of a globally recognized forum has hindered the ability to define pressing scientific goals, plan in the long term—which is counterproductive for the more complex theoretical and modeling tasks—highlight key achievements, and support both the career development of early-career scientists and the recognition of individuals who have made fundamental contributions to the field. It would also ensure a return on investment for the contributions that Europe has made to DUNE and Hyper-Kamiokande. **We believe that establishing a dedicated center based at CERN and serving the broader community of neutrino physicists would represent a significant step forward**. Such a center would act as a forum for cross-experiment and experiment-theory discussion, to exchange ideas, knowledge as well as methods. It would provide a strategic framework to foster collaboration, and support talent development—especially critical for countries with small or just developing neutrino communities—and to prepare for the era of high-statistics, high-resolution data. In that respect, the center would also be very important for the ongoing CERN neutrino experiments at the LHC, which aim for high-statistics cross section measurements.

2.3 DUNE and Hyper-Kamiokande

CERN is a core DUNE institution, and the experiment's success is linked to its long-term commitment. CERN not only fostered the demonstration of the DUNE technologies but it also provides crucial expertise and financial support for the realization of key components such as the two membrane cryostats for the Far Detectors, and detector systems, like High Voltage, Trigger and Data Acquisition, and Charge Readout. DUNE Phase-II is essential to achieve the ultimate precision of the experiment by adding the third and fourth modules, the near detector upgrade and the increase of beam power, thus reaching the ultimate sensitivity. The DUNE community strongly relies on the forthcoming ProtoDUNE runs to validate the technologies that will be employed in the third and fourth modules and the deployment of the corresponding cryostats, as well as developments targeting technologies of the upgrade of the Near Detector. Hyper-Kamiokande has benefited and is benefiting from the NP07, the Water Cherenkov Test Experiment (WCTE), and NP08 projects to establish its physics program and construction plan. It is preparing for the high-statistics phase, after 2030, and is developing the conceptual design of the final upgrade of ND280, named ND280++, to achieve the ultimate precision in the measurement of the leptonic CP violating phase. Building on the success of NP07, such project would largely benefit from the support of the Neutrino Platform. Indeed, experiments—such as T2K—have proved that an excellent near detector (ND) is required to exploit the full physics potential of long-baseline experiments through providing cross section and flux measurements. Both Hyper-Kamiokande and DUNE are planning additional upgrades of their NDs with significant European contributions. **A steady commitment from CERN to all these initiatives in anticipation of the DUNE and Hyper-Kamiokande run should thus remain a top priority for the European groups.**

2.4 Neutrino cross sections

During the last decade, clear advances have been achieved on cross sections and further data will come from the near detectors of DUNE and Hyper-Kamiokande, together with the Fermilab SBN program. Still, major open questions remain to be explored, which require new technologies and facilities, and a refined theory program for neutrino-nucleus cross sections. While CERN does not provide a high-intensity neutrino beam dedicated to oscillation physics, its versatile infrastructure is well-suited to making unique and significant contributions to neutrino cross-section studies. This potential spans both the energy range relevant for Hyper-Kamiokande and DUNE as well as the high-energy domain extending toward the IceCube/ANTARES/KM3NeT scale. The scientific benefits of such a program are invaluable. Neutrino cross sections remain among the least well-known properties of neutrinos, and this gap in knowledge poses significant challenges to achieving ultimate precision in experiments. Furthermore, it limits our ability to fully understand electroweak interactions within the nuclear medium.

On one hand, this can be achieved by promoting the design and implementation of a high-precision neutrino beam, featuring monitored and tagged neutrinos (SBN@CERN) to enable unprecedented accuracy at the GeV scale. In particular, a high-statistics tagged neutrino sample providing identification of neutrino energy on an event-by-event basis would allow for a transformative BSM and cross section program, including measurements of neutrino energy smearing and crucial kinematic quantities usually only accessible in electron scattering experiments. It is important to note that the proposed SBN@CERN program is a completely novel facility based on monitored and tagged neutrinos as described above, with a distinct scope, timescale, and physics potential that is complementary to the Fermilab SBN program.

Additionally, CERN should consolidate the unique opportunities provided by SHiP/NA67 and by the High-Luminosity LHC through upgrades to the FASER and SND@LHC experiments, and potentially through the development of the Forward Physics Facility (FPF). If not exploited now, the opportunities at the LHC to measure cross sections of all three neutrino flavors at TeV energies, e.g., for testing lepton flavor universality or exploring the gluon distribution in the proton at momentum fractions x below even 10^{-5}, will disappear for decades until the next multi-TeV collider is realized. In that respect, the FPF experiments would collect millions of neutrino interactions at the highest man-made energies. It should be stressed that the LHC neutrino beam is readily available whenever the LHC is operational with no additional cost or infrastructure needed to produce it, and whose exploitation in also different setups continues to be investigated.

We believe CERN should actively pursue a leadership role in the area of neutrino cross sections over the next decade.

2.5 Hadroproduction experiments

Hadroproduction experiments have proven to be extremely reliable and have represented a paradigm shift in our understanding of neutrino fluxes since the discovery of neutrino oscillations. CERN has established a strong leadership position in this field. NA61/SHINE has been providing fundamental input for long-baseline experiments and has a solid experimental program until LHC Long Shutdown 3 (LS3). We recognize the opportunities and needs for a post-LS3 run of this experiment. A potential lower-energy beamline (1-13 GeV) would allow for important new measurements tailored to some of the largest remaining accelerator and atmospheric neutrino flux uncertainties, alongside potential new constraints on the secondary interactions of hadrons produced in neutrino interactions. **We strongly encourage further support of these activities as well as the strengthening of the Collaboration including the active involvement of Hyper-Kamiokande and DUNE physicists to conduct adequate hadroproduction studies that can be readily integrated into the early runs of their long-baseline experiments**. DsTau/NA65 measures forward charm production at the SPS, which will significantly constrain charm and thus neutrino flux uncertainties for the SHiP/NA67 neutrino program, as well as constrain hadronic interaction models used to predict atmospheric neutrino fluxes. Furthermore, one of the main goals of the LHC neutrino program is to constrain hadro-production at the highest energies through neutrino fluxes, which serves as input for the astro-particle community to resolve the cosmic ray muon puzzle—an outstanding discrepancy between current hadro-production models and observations—as well as to constrain the prompt atmospheric neutrino flux. **We recognize the unique role of CERN and its facilities for a significant advancement in hadroproduction measurements.**

2.6 Cross-fertilization

CERN has established a robust framework for detector R&D within the context of the DRD Collaborations that are beneficial to both experiments under construction, like DUNE and Hyper-Kamiokande, and proposed facilities, like ESSnuSB, SBN@CERN, and nuSTORM. DRD1, 2, and 4 are of great relevance since they envisage technologies that will be employed in the near and far detectors of long-baseline experiments. DRD2, in particular, addresses the technical challenges and novel opportunities for large-mass liquid detectors, including liquid argon and water Cherenkov neutrino detectors. We advocate for the active participation of accelerator neutrino physicists in the DRD activities, especially on items relevant to Hyper-Kamiokande and DUNE Phase II. Similarly, CERN supports advances in muon colliders, which are inherently powerful neutrino sources that can be staged to provide facilities with ν_e yields far exceeding those available in conventional beams. Some of these challenges have been addressed by the nuSTORM Collaboration. Their findings could contribute to the phased development of a Muon Collider and its Demonstrator, as well as introduce a new technology based on stored muons to enable high-statistics ν_e neutrino-nucleus scattering studies. Likewise, a Gamma Factory facility could be used as a source of flavor-tagged neutrinos. **We strongly support the DRD programmes and we are keenly following the development of the Muon Collider and other non-conventional facilities to identify any opportunities for an intense ν_e source that can complement the aforementioned neutrino cross section program**.