

Input document for the European Particle Physics Strategy

A high precision neutrino beam for a new generation of short baseline experiments

The ENUBET Collaboration¹

Abstract

The current generation of short baseline neutrino experiments is approaching intrinsic source limitations in the knowledge of flux, initial neutrino energy and flavor. A dedicated facility based on conventional accelerator techniques and existing infrastructures designed to overcome these impediments would have a remarkable impact on the entire field of neutrino oscillation physics. It would improve by about one order of magnitude the precision on ν_μ and ν_e cross sections, enable the study of electroweak nuclear physics at the GeV scale with unprecedented resolution and advance searches for physics beyond the three-neutrino paradigm. In turn, these results would enhance the physics reach of the next generation long baseline experiments (DUNE and Hyper-Kamiokande) on CP violation and their sensitivity to new physics. In this document, we present the physics case and technology challenge of high precision neutrino beams based on the results achieved by the ENUBET Collaboration in 2016-2018. We also set the R&D milestones to enable the construction and running of this new generation of experiments well before the start of the DUNE and Hyper-Kamiokande data taking. We discuss the implementation of this new facility at three different level of complexity: ν_μ narrow band beams, ν_e monitored beams and tagged neutrino beams. We also consider a site specific implementation based on the CERN-SPS proton driver providing a fully controlled neutrino source to the ProtoDUNE detectors at CERN.

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1 Introduction

Over the last 50 years, accelerator neutrino beams [1] have been developed toward higher and higher intensities but uncertainties in the flux, flavor composition and initial neutrino energy are still very large. Thanks to the enormous progress in neutrino scattering experiments [2, 3], the measurements of neutrino cross sections are now limited by the knowledge of the initial fluxes, since the yield of ν_μ is not measured in a direct manner but relies on extrapolation from hadro-production data and a detailed simulation of the neutrino beamline. This limitation bounds the precision that can be reached in the measurement of the absolute cross sections to $\mathcal{O}(5-10\%)$. In addition, current experiments reconstruct the neutrino energy from final state particles. As a consequence, the reconstructed energy and, in turn, the measurement of the cross section is affected by model dependencies. Finally, pion-based sources mainly produce ν_μ while most of the next generation oscillation experiments will rely on the appearance of ν_e at the far detector. A direct measurement of the ν_e cross sections is, hence, of great value for the current (T2K, NO ν A) and forthcoming (DUNE, Hyper-Kamiokande) long-baseline experiments [4].

The aim of this document is to:

- present the physics case of a dedicated narrow-band beam, which addresses precision neutrino physics at short baselines;
- foster a vigorous R&D programme to enable the construction and running of a new generation of cross section experiments well before the start of the DUNE and Hyper-Kamiokande data taking;
- pave the road for a CERN-based facility dedicated to high precision neutrino scattering physics. This facility will run in parallel with DUNE and Hyper-Kamiokande. It will thus enhance the physics reach of long-baseline experiments (in particular CP reach and non-standard neutrino oscillation physics) reducing in a substantial manner their leading systematic contributions.

We will discuss three implementations of high precision conventional (i.e. pion/kaon based) neutrino beams, at different level of complexity and cost. Non conventional facilities based on muon storage and decay are beyond the scope and timeline considered in this document and we refer to [5, 6] for additional insights on these technologies.

High precision cross section physics motivated the development of “monitored neutrino beams” [7] and, in turn, the ENUBET proposal [8, 9]: a facility where the only source of electron neutrino is the three body semileptonic decay of kaons: $K^+ \rightarrow \pi^0 e^+ \nu_e$ (K_{e3}). Most of the results presented in this document has been achieved by the ENUBET Collaboration in 2016-2018. The ERC ENUBET (“Enhanced NeUtrino BEams from kaon Tagging”) project [10] is aimed at building a detector that identifies positrons in K_{e3} decays while operating in the harsh environment of a conventional neutrino beam decay tunnel. The project addresses all accelerator challenges of monitored neutrino beams: the proton extraction scheme, focusing and transfer line, instrumentation of the decay tunnel and the assessment of the physics performance. This technique is currently the most promising method to fulfill simultaneously all the requirements for high precision ν_μ and ν_e cross section measurements.

The ENUBET activities are embedded in a larger community effort to improve our knowledge of neutrino properties and perform ancillary measurements for the next generation long baseline experiments. This framework is detailed in a dedicated input document for the European Strategy [5].

2 The physics of high precision neutrino beams

High precision neutrino beams are facilities that provide a control of the neutrino flux at source with 1% level precision and the beam energy spread constrains the initial neutrino energy within $\sim 10\%$.

2.1 GeV scale interactions of neutrinos with matter

When coupled to fine grained neutrino detectors, this facility could unravel the complexity of neutrino interactions at the GeV scale [3]: quasi-elastic interactions, resonance production, meson exchange (multi-nucleon) and, at higher energies, the onset of deep inelastic scattering off quarks (see Fig. 1 left, from [4]). In ENUBET a superior level of control is achieved reducing the overall normalization uncertainty in the flux and introducing the constraint on the incoming energy through the narrow-band off-axis technique (NBOA - see Sec. 3).

This is particularly remarkable for the study of electron neutrino cross sections. Fig. 1 (right) shows the present measurements of the ν_e^{CC} cross section. Conventional beams are designed to minimise the ν_e contamination in order to reduce the background in the far detector. Hence, the direct measurements of the ν_e cross sections are based on samples that are 2-3 orders of magnitude smaller than for ν_μ and affected from larger uncertainties coming from both the flux and detector response [11], [12]. The next generation of near detectors for DUNE and Hyper-Kamiokande will make available larger samples so that ν_e results will soon be systematic limited. At that time, the impact of a high precision neutrino beam as ENUBET will be remarkable: it is summarized in Fig. 1. Measurements for electron antineutrinos are even more challenging, due to the lower cross sections involved and the complete lack of measurements from current experiments. The ENUBET negative polarity run will thus provide the first precision measurement of $\sigma_{\bar{\nu}_e}$ with a relative precision of $< 5\%$.

2.2 Search for new physics

Disentangling models of new physics from the 3-flavour model (i.e. sterile neutrinos, Non-Standard-Interactions - NSI -, unexpected phenomena) requires mastering both the normalization and the spectrum of the neutrino interaction rates [13]. High precision beams in the DUNE/Hyper-Kamiokande era will impact on this field both indirectly and directly. A high precision measurement of ν_e cross sections is mandatory in the presence of NSI [12, 14, 15], at long-baseline experiments. Assuming only standard interactions and exploiting cancellation of correlated uncertainties between the ν_e and ν_μ channels, the expected number of electron neutrino interactions at far detectors can currently be predicted with $\sim 5\%$ uncertainty [16] due to the uncertainty of the σ_e/σ_μ ratio. A percent level precision in the measurement

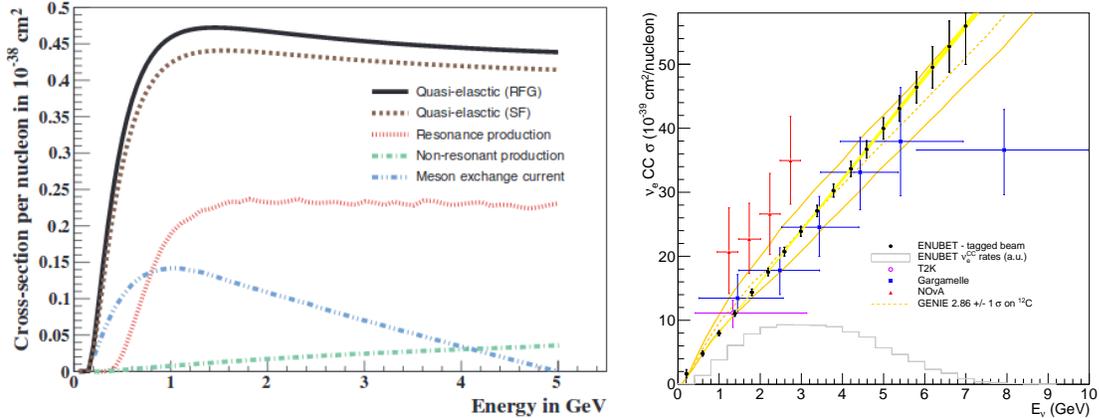


Figure 1: Left: neutrino interaction processes at the GeV scale (from [4]). Right: present status of the electron neutrino cross section measurements (Gargamelle, NO ν A, T2K), theory expectation (GENIE) and projected measurements from ENUBET in one year of data taking with Protodune-SP.

of the σ_e and σ_μ cross sections will therefore enhance remarkably the sensitivity of future long-baseline experiments to non standard effects.

In addition, ENUBET will become the most urgent facility if the Miniboone/LSND ν_e excess [17] is confirmed by the Fermilab Short Baseline programme. ENUBET provides a complete control of the flavor at source and the NBOA technique gives access to the oscillation pattern with a single detector in most of the allowed Miniboone/LSND parameter space.

2.3 Systematics reduction for the CP violation measurement

A high precision neutrino source is a key asset for the measurement of CP violation in the leptonic sector. CP violation is the core of the physics programme at future long-baseline facilities (DUNE, Hyper-Kamiokande, ESSnuSB) where the δ_{CP} accuracy relies on the possibility of performing a precise determination of the rate of ν_e at far detectors to pin down all the parameters of the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities. The impact of systematics in the CP discovery reach has been outlined in several works [18, 19]. Thanks to larger detectors and new or upgraded beams the overall statistical error on appearance events will finally reach the 1-2% level [20] thus becoming smaller than the systematic uncertainty we can expect as of today.

The number of observed ν_e^{CC} candidate events at the far detector can be expressed as:

$$N_F(\nu_e) \propto \sum_j \left(\int \phi_F(\nu_\mu) P(\nu_\mu \rightarrow \nu_e) \sigma_{j,\nu_e}^{CC} \epsilon_j dE_\nu + B_j \right) \quad (1)$$

where j indicates the interaction mechanisms and all terms (flux ϕ , cross sections σ , efficiency ϵ , oscillation probability P) depend on the neutrino energy E_ν over which the integral is performed. The term B is the background which, as well as for genuine signal events, also

depends on the knowledge of the cross sections, the (oscillated) flux and the detector response. Background is mostly due to the intrinsic ν_e component in the initial flux and Neutral Current (NC) events with π^0 production. The extraction of the physics encoded in the oscillation probability term $P(\nu_\mu \rightarrow \nu_e)$ is thus intertwined with the knowledge of cross sections and their energy dependence.

The near detectors constrain the product of the unoscillated flux and the neutrino cross sections (event rate at near detector) and predict the rates at the far detector. At first approximation, the near-far detector comparison cancels nuisance parameters that are not due to oscillation. The size of second order corrections, however, is too large for the DUNE and HK era. These corrections account for differences in the near and far detector fluxes (due to finite distance effects), acceptances (different detector and fiducial volumes), background, pile-up effects due to the different neutrino rates and, in some cases, the different nuclear average composition. These factors can be mitigated building a “far enough” near detector (intermediate detector) with the same detector technology of the far detector. Still the composition of processes involved in the background is different at the near and far site because the spectrum of ν_μ interactions is very different in the two locations due to ν_μ disappearance. Far detectors are designed to maximize the statistics of signal events. The designs of near detectors in long-baseline experiments aim to provide much more detailed information on event kinematics, which is mandatory to reduce uncertainties on fluxes, interaction models and backgrounds. As a consequence, the near and far detectors employ quite often different technologies [21], [22], [23].

The T2K Collaboration has been able to reduce the corresponding uncertainties in the far detector rates down to 5-6% in the $\nu_\mu \rightarrow \nu_\mu$ disappearance channel and $\nu_\mu \rightarrow \nu_e$ appearance channel [16]. The procedure of energy unfolding is quite involved: the link between the observed event kinematics and the neutrino energy is poorly known due to the lack of precise cross sections measurements. For this reason, in most cases experiments provide flux integrated cross sections as a function of variables that can be measured in a straightforward manner, as the kinematical variables of the produced lepton. A workaround is offered by the above-mentioned NBOA technique that provides a link between the (narrow) energy spectrum of the neutrinos and the location of the neutrino interaction vertex at the detector.

In $\nu_\mu \rightarrow \nu_e$ appearance measurements, additional sources of systematics arise from the difference in the final and initial neutrino flavors. The near-to-far event distribution ratio thus depends on the σ_e/σ_μ cross section ratio. This ratio could be affected by the second-class currents or deviations from the standard parameterization of the pseudoscalar terms and, in general, it is not measured in a direct manner.

The ENUBET approach consists in having a facility to measure the cross sections as a function of energy with much better precision by removing the flux normalization error and measuring a priori the energy spectrum of neutrinos using an easy to reconstruct correlated variable (radial distance of the vertex from the beam axis). This experimental strategy can be implemented with a dedicated low intensity beam and a near detector employing the same detection technology as DUNE and HK.

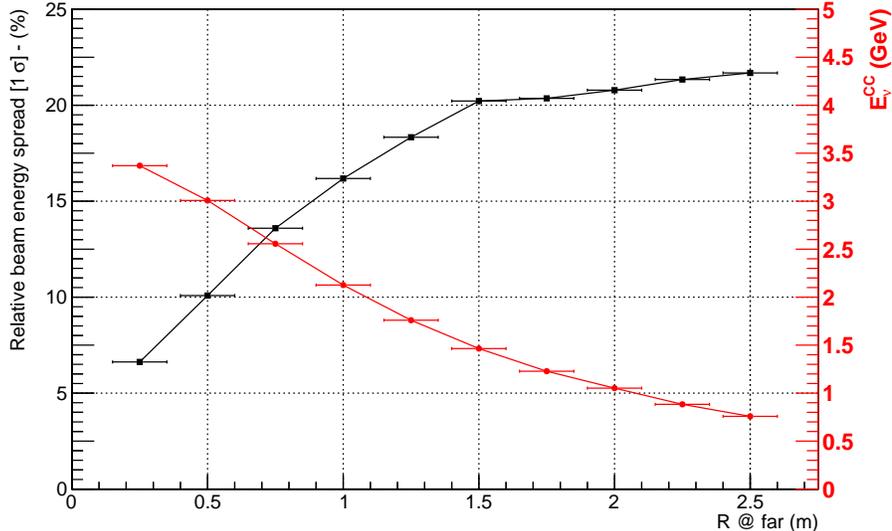


Figure 2: Beam energy spread (in black) and peak energy (in red) as a function of the distance R of the interaction vertex at the detector from the beam axis.

3 ν_{μ} cross section measurements

Narrow-band beams are the ideal tool to perform high precision ν_{μ} scattering measurements since they provide a source where the energy of the neutrino is known a priori with an uncertainty of $\sim 10\%$. The most striking drawback of narrow band beams is the limited energy range covered by the neutrino source. Unfortunately, the next generation of long baseline experiments requires a broad energy coverage from 0.5 GeV to about 5 GeV. The most effective way to increase the energy range spanning the entire region of interest for DUNE and HK (0.5-5 GeV) is to employ the off-axis technique [24] in a single detector [25] using a neutrino beam where pions and kaons are selected by a transfer line with a narrow momentum bite. This technique has been developed by ENUBET in 2018 and can be implemented using existing detectors as ProtoDUNE-SP and ProtoDUNE-DP at CERN.

The “narrow band off-axis” (NBOA) technique [26] exploits the strong correlation between the energy of the neutrino interacting in the detector and the radial distance (R) of the interaction vertex from the beam axis in a 10% momentum bite beam. The incoming neutrino energy is determined with a precision given by the pion peak width of the spectrum at a fixed R . In a transfer line optimized for the DUNE energy range (momentum of secondaries: 8.5 GeV), it ranges from 7% at 3.5 GeV to 22% at 0.8 GeV, as illustrated in Fig. 2. Only a loose cut on the visible energy is needed to separate the ν_{μ} from pion decay from the ν_{μ} originating from the two body kaon decay. This cut is not needed if the transfer line is optimized for the Hyper-Kamiokande energy range (momentum of secondaries below 4 GeV) since the kaon production is kinematically suppressed. In this way, differential cross section measurements can be performed without relying on the reconstruction of the final state products for the determination of the neutrino energy.

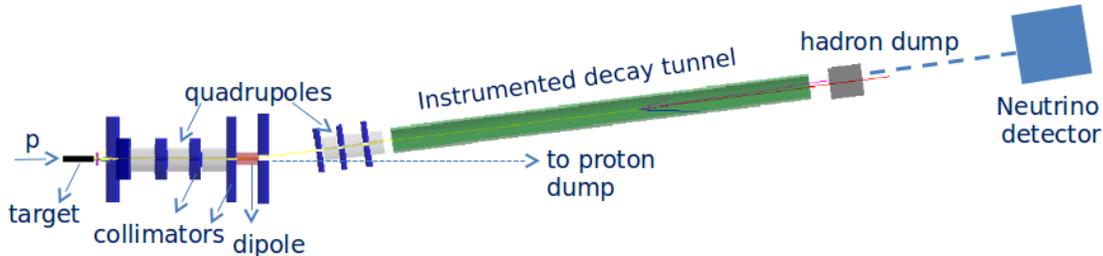


Figure 3: Schematics of the ENUBET neutrino beam in the static focusing option (not to scale).

The simplest implementation of this facility is based on a conventional fast extraction ($10 \mu\text{s}$) horn over a narrow band transfer line. This configuration can be implemented at CERN SPS (400 GeV protons) and brings $77 \times 10^{-3} \pi^+$ per proton-on-target (pot) for a single dipole, two triplet transfer line with a central momentum of 8.5 GeV. This facility requires 1.1×10^{19} pot to produce $1.1 \times 10^6 \nu_\mu$ charged current (CC) events in ProtoDUNE-SP. Due to the presence of the transfer line and the large instantaneous currents produced during the fast extraction, the number of secondaries reaching the decay tunnel can be measured by beam current transformers with a precision of $\sim 1\%$. Hence, the measurement of the ν_μ flux does not rely on simulation and hadroproduction data except for the correction due to transported protons and kaons.

This configuration is compatible with current CERN North Area infrastructures and with the size and position of ProtoDUNE-SP and ProtoDUNE-DP in EHN1. Studies are ongoing to ascertain the overall systematic budget on ν_μ cross section measurements and, more generally, the opportunities offered by this facility on short baseline neutrino physics [27].

4 ν_e cross section measurements

A monitored neutrino beam is the ideal tool to measure neutrino cross sections at percent level precision. It combines the above-mentioned NBOA technique with a direct measurement of the ν_e flux and provides a fully controlled source of ν_e at the GeV scale.

The ENUBET neutrino beam (see Fig. 3) is a conventional narrow band beam with a short (~ 20 m) transfer line followed by a 40 m long decay tunnel. Unlike most of the beams currently in operation, the decay tunnel is not located in front of the focusing system (horns) and the proton extraction length is slow: a few ms in the horn option and 2 s in the static focusing option (see below). Particles produced by the interaction of protons on the target are focused, momentum selected and transported at the entrance of the tunnel. Non-interacting protons are stopped on a proton beam dump.

The particles that reach the decay tunnel are hence pions, kaons and protons within the momentum bite of the transfer line (10% in ENUBET). Off-momentum particles are mostly

low energy pions, electrons, positrons and photons from tertiary interactions in the collimators and other components of the beamline, and muons from pion decay that cross the collimators. Due to the presence of the transfer line and the long proton extraction time (> 2 ms), the rate of these particles are several orders of magnitude smaller than beams currently in operation and the instrumentation located in the decay tunnel can monitor lepton production at single particle level.

Kaon decays are particularly well suited for single-particle monitoring. In the current ENUBET design (tuned for the energy range of interest of DUNE) the mean energy of the hadrons selected in the transfer line (8.5 GeV) and the length of the decay tunnel is optimized in order to have only one source of electron neutrinos: the K_{e3} decay of the kaons - $K^+ \rightarrow \pi^0 e^+ \nu_e$. Electron neutrinos from the decay in flight of kaons represent $\sim 97\%$ of the overall ν_e flux. Since the positrons are emitted at large angles with respect to muons from pion decay, particles produced by the kaons reach the wall of the instrumented tunnel before hitting the hadron dump (see Fig. 3). The vast majority of undecayed pions, particles transported along the transfer line and muons from $\pi^+ \rightarrow \mu^+ \nu_\mu$ reach the hadron dump without hitting the walls and do not contribute to the particle rate in the instrumented walls.

The rate of positrons from K_{e3} decays is monitored at single particle level by longitudinally segmented calorimeters that separate positrons from pions, muons, neutrons and protons. The modules of the calorimeter are located inside the beam pipe and are assembled into cylindrical layers. Positron/photon separation is performed by a photon veto made of plastic scintillator tiles located just below the innermost layer.

Particle rates in the instrumented walls are sustainable only if the proton extraction is $\gg 10 \mu\text{s}$. ENUBET is considering two focusing options. The first option is based on a magnetic horn that is pulsed for 2-10 ms and cycled at several Hz during the accelerator flat-top. This option has a very large acceptance producing at SPS $77 \times 10^{-3} \pi^+/\text{pot}$ and $7.9 \times 10^{-3} K^+/\text{pot}$. The proton extraction scheme (“burst mode extraction”) has been studied at the CERN-SPS in 2018 and will be commissioned after the LHC Long Shutdown 2. In summer 2018, ENUBET also demonstrated the effectiveness of a purely static focusing system based on DC operated magnets. The static option allows for slow proton extractions (2-4 s) reducing by two order of magnitude the rate at the instrumented decay tunnel. Static focusing is the ideal focusing scheme for any monitored neutrino beam and paves the way (see below) to the first tagged neutrino beam. It has, however, a smaller acceptance than the horn-based system producing $19 \times 10^{-3} \pi^+/\text{pot}$ and $1.4 \times 10^{-3} K^+/\text{pot}$. As a consequence, it requires about 4.5×10^{19} pot at the SPS to carry out the cross section program both with ν_e and ν_μ . Similarly, the cosmic ray veto system of the ProtoDUNE detectors should be improved to suppress cosmic ray background without relying on beam timing information.

In ENUBET, the rate of positrons provides a direct measurement of the ν_e produced in the tunnel. The distribution of particles (positron, muons, pions) along the axis of the tunnel and their energy and polar angle distribution constrain any source of systematic bias between the rate of positrons observed in the tunnel and the expected rate of ν_e at the detector. Unlike present beams, at leading order no information is needed from particle production yields in the target (hadro-production), the simulation of transport and reinteraction of secondary particles in the beamline, the monitoring of the protons on target and of the currents in the horn because the rate of particle production in the tunnel provides an observable that is

directly linked to the flux. ENUBET is now studying sub-leading effects to demonstrate that the total systematic budget of the ν_e flux is below 1%.

Since the K_{e3} branching ratio is known with a precision of 0.8%, positron monitoring also provides the total production rate of kaons at the per-cent level. This precision can be further improved monitoring the rate of pion production in the tunnel due to the other decay modes of kaons and, in particular, the leading $K^+ \rightarrow \mu^+ \nu_\mu$ (BR \simeq 63%) and $K^+ \rightarrow \pi^+ \pi^0$ (BR \simeq 21%). These channels, which were not included in the original physics programme of ENUBET, are now exploited to evaluate the flux of ν_μ from kaons. Finally, a direct measurement of the rate of muons from π^+ decays after the hadron dump cannot be done at single particle level for the horn-based option but it can be performed if the focusing is purely static because the muon rate is reduced by two order of magnitudes. In this case, the muon rate after the hadron dump provides the ν_μ flux from pion decays with a precision comparable with the ν_e flux.

ENUBET can be operated in inverse-polarity mode, producing $\bar{\nu}_e$ from $K^- \rightarrow \pi^0 e^- \bar{\nu}_e$ and $\bar{\nu}_\mu$ from $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ and $K^- \rightarrow \mu^- \bar{\nu}_\mu$. All considerations above apply to ENUBET as a source of electron and muon anti-neutrinos.

5 Tagged neutrino beams

A purely static focusing system opens up several opportunities beyond the original goals of ENUBET. Since the proton extraction can be diluted up to several seconds, the instantaneous rate of large angle decay products in the decay tunnel is reduced by about two orders of magnitude compared with the horn option. In the ENUBET static option the time between two K_{e3} decays is 1.3 ns, which can be further increased operating with a 4 s extraction or a smaller number of pot per cycle. The occurrence of a neutrino interaction in the detector can thus be time linked with the observation of the lepton in the decay tunnel. Such an observation has never been performed in any neutrino experiment at any energy and would represent a major breakthrough in experimental neutrino physics. A facility where the neutrino is uniquely associated with the other decay particles of the parent kaon is called a “tagged neutrino beam”. Physicists have speculated about this possibility just after the first direct observation of neutrinos [28, 29] but the technologies that provide time resolution, pile-up mitigation and radiation hardness for time tagged neutrino beams are available since a few years only. In order to suppress accidental coincidences between the neutrino interaction and uncorrelated particles inside the beam pipe, the timing precision of the detectors that are used to instrument the decay tunnel must reach 100 ps. This precision is needed also to associate the positron with the other decay products of the kaons. The timing precision of the neutrino detector should not exceed a few ns, as well. The physics potential of tagged neutrino beams are outstanding since they provide energy and flavor measurement on an event-by-event basis and are the ideal tool to study cross sections and non standard oscillation phenomena, including sterile neutrinos. For the first time, they also give experimental access to the lepton-neutrino entangled state to study propagation and collapse of the wavefunction. A CERN based implementation requires an improvement of the timing resolution of the ProtoDUNE Photon Collection System up to \sim 1 ns and a significant R&D effort since this technology is not mature as the monitored neutrino beams.

6 Conclusions

Neutrino oscillation physics gathers one of the largest community in particle physics and CERN is playing a leading role in the construction of next generation long baseline neutrino experiments. The physics reach of these experiments can be substantially enhanced by percent level precision measurements of the ν_μ and ν_e cross sections. These precisions are mandatory to extract oscillation parameters and non-standard effects from the rate of ν_e and ν_μ at the far detector of DUNE and Hyper-Kamiokande. They also ground on solid base our understanding of electroweak nuclear physics and the forthcoming results on CP violation in the leptonic sector. A dedicated short baseline facility for a new generation of cross section experiments is therefore the most cost-effective completion of the long-baseline programme. A high precision narrow band beam with lepton monitoring at single particle level is the ideal tool for systematic reduction in the DUNE and Hyper-Kamiokande era and will bring to a major leap in our knowledge of neutrino cross sections. CERN is the natural candidate to host such facility at SPS given the outstanding particle identification capability, energy resolution and fiducial mass of the liquid argon detectors operated in EHN1.

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