A CERN-based high-intensity high-energy proton source for long baseline neutrino oscillation experiments with next-generation large underground detectors for proton decay searches and neutrino physics and astrophysics

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Abstract
The feasibility of a European next-generation very massive neutrino observatory in seven potential candidate sites located at distances from CERN ranging from 130 km to 2300 km, is being considered within the LAGUNA design study. The study is providing a coordinated technical design and assessment of the underground research infrastructure in the various sites, and its coherent cost estimation. It aims at a prioritization of the sites within summer 2010 and a start of operation around 2020. In addition to a rich non-accelerator based physics programme including the GUT-scale with proton decay searches, the detection of a next-generation neutrino superbeam tuned to measure the flavor-conversion oscillatory pattern (i.e. 1st and 2nd oscillation maxima) would allow to complete our understanding of the leptonic mixing matrix, in particular by determining the neutrino mass hierarchy and by studying CP-violation in the leptonic sector, thereby addressing the outstanding puzzle of the origin of the excess of matter over antimatter created in the very early stages of evolution of the Universe. We focus on a multi-MW-power neutrino superbeam (="hyperbeam") produced by high-intensity primary protons of energy 30÷50 GeV.

We argue that this option is an effective way to establish long baseline neutrino physics in Europe with the high-stake prospects of measuring \( \theta_{13} \) and addressing CP-violation in the leptonic sector.

1 Physics goals

Large underground neutrino detectors, like SuperKamiokande [1] and SNO [2], have achieved fundamental results in particle and astro-particle physics. The construction in Europe of next-generation very large multipurpose neutrino observatory of a total mass in the range of 100’000 to 1’000’000 tons devoted to particle and astroparticle physics was recently discussed [3]. Such a massive detector will provide new and unique scientific opportunities in this field, likely leading to fundamental discoveries, and is currently listed as one of the priority of the ASPERA roadmap defined in 2008 [4].

The FP7 Design Study LAGUNA [5] (Large Apparatus studying Grand Unification and Neutrino Astrophysics) is a EC-funded project carrying on underground sites investigations and design for such an observatory. Three detector options are currently being studied: GLACIER [6], LENA [7], and MEMPHYS [8].

The new observatory aims at a significant improvement in the sensitivity to search for proton decays, pursuing the only possible path to directly test physics at the GUT scale, extending the proton (and bound neutron) lifetime sensitivities up to \( 10^{35} \) years, a range compatible with several theoretical models [9]: moreover it will detect neutrinos as messengers from astrophysical objects as well as from the

*Based on a document submitted to the CERN SPC Panel on Future Neutrino Facilities (November 2009).
Early Universe to give us information on processes happening in the Universe, which cannot be studied otherwise. In particular, it will sense a large number of neutrinos emitted by exploding galactic and extragalactic type-II supernovae, allowing an accurate study of the mechanisms driving the explosion. The neutrino observatory will also perform precision studies of other astrophysical or terrestrial sources of neutrinos like solar and atmospheric ones, and search for new sources of astrophysical neutrinos, like for example the diffuse neutrino background from relic supernovae or those produced in Dark Matter (WIMP) annihilation in the centre of the Sun or the Earth.

Coupled to advanced neutrino beams from CERN, it would measure with unprecedented sensitivity the last unknown mixing angle $\theta_{13}$, determine the neutrino mass hierarchy and unveil the existence of CP violation in the leptonic sector, which in turn could provide an explanation of the matter-antimatter asymmetry in the Universe.

2 Main goal of the LAGUNA design study

Europe currently hosts four national underground laboratories located resp. in Boulby (UK), Canfranc (Spain), Gran Sasso (Italy), and Modane (France), with detectors looking for Dark Matter or neutrino-less double beta decays, or performing long-baseline experiments. However, none of these existing laboratories is large enough for the next-generation very massive neutrino experiments. The LAGUNA design study is therefore evaluating possible extensions of the existing deep underground laboratories, and on top of it, the creation of new laboratories in the following regions: Umbria Region (Italy), Pyhäsalmi (Finland), Sierozsowice (Poland) and Slanic (Romania).

Table 1 summarizes some basic characteristics of the sites under consideration. It also lists their distance from CERN and the neutrino energies corresponding to the first maximum of the oscillation for the present estimate of the mass squared difference $\Delta m_{23}^2 \sim 2.5 \times 10^{-3}$ eV$^2$. These are relevant to optimize the energy spectrum of the neutrino beam. In order to consider all possible baselines, the new CERN neutrino superbeam should provide neutrinos in an energy range $0 \div 7$ GeV. The actual optimization depends of course on the chosen site.

| Location         | Type             | Envisaged depth m.w.e. | Distance from CERN [km] | Energy 1st Osc. Max. [GeV] |
|------------------|------------------|------------------------|-------------------------|---------------------------|
| Fréjus (F)       | Road tunnel      | $\simeq 4800$          | 130                     | 0.26                       |
| Canfranc (ES)    | Road tunnel      | $\simeq 2100$          | 630                     | 1.27                       |
| Umbria (IT)      | Road tunnel      | $\simeq 1500$          | 665                     | 1.34                       |
| Sierozsowice (PL)| Green field      | $\simeq 2400$          | 950                     | 1.92                       |
| Boulby (UK)      | Salt Mine        | $\simeq 2800$          | 1050                    | 2.12                       |
| Slanic (RO)      | Salt Mine        | $\simeq 600$           | 1570                    | 3.18                       |
| Pyhäsalmi (FI)   | Mine             | up to $\simeq 4000$    | 2300                    | 4.65                       |

$^a$ $\simeq 1.0^\circ$ CNGS off axis.

Site selection is a complex process involving the optimization and assessment of several parameters, encompassing physics performance, technical feasibility, safety and legal aspects, socio-economic and environmental impact, costs, etc. As a result, LAGUNA is an interdisciplinary study, involving most European physicists interested in the physics of massive underground neutrino detectors, as well as geo-technical experts, geo-physicists, structural engineers, mining engineers and also large storage tank engineers. It regroups 21 beneficiaries, composed of academic institutions from Denmark, Finland, France, Germany, Poland, Spain, Switzerland, United Kingdom, as well as industrial partners specialized in civil and mechanical engineering and rock mechanics, commonly assessing the feasibility of this research Infrastructure in Europe.

The study, which started during the summer 2008, is well advanced and interim reports for each
of the seven sites are being compiled\textsuperscript{1}. Several documents will be published within the end of the study. The consortium intends to converge to a prioritized list of sites within the summer 2010.

3 Frontier technologies for next generation neutrino detectors

The search for proton decays with lifetimes up to \(10^{35}\) years as well as the measurement of the unknown mixing angle \(\theta_{13}\) and the prospects to discover CP-violation in the leptonic sector and to determine the neutrino mass hierarchy, make clear that the next generation neutrino experiments will be more ambitious than previous ones.

European groups are actively engaged in the R&D in technologies based on large volume liquids for future neutrino detectors, although this work is not funded as part of the LAGUNA design study. We briefly describe these activities, subdivided into the three different detector options:

– **Water Cerenkov Imaging Detector**: MEMPHYS is envisioned as a 0.5 Mton scale detector extrapolated from the Super-Kamiokande and consisting of 3 separate tanks of 65 m in diameter and 65 m height each. Such dimensions meet the requirements of light attenuation length in (pure) water and hydrostatic pressure on the bottom PMTs. A detector coverage of 30\% can be obtained with about 81’000 PMT of 30 cm diameter per tank. MEMPHYNO \textsuperscript{10} is one R&D item in Europe whose main purpose is to serve as test bench for new photo-detection and data acquisition solutions. Based on the extensive experience of Super-Kamiokande, this technology is best suited for single Cerenkov ring events typically occurring at energies below 1 GeV.

– **Liquid Argon Time Projection Chamber (LAr TPC)**: application of this technology, originally developed at CERN, to large detectors was pioneered in Europe by the ICARUS effort which culminated in the successful operation of half-T600 on surface \textsuperscript{11}. After several years of installation at LNGS, underground operation of T600 is expected soon. GLACIER is a proposed scalable concept for single volume very large detectors up to 100 kton. The cryostat is based on industrial liquefied natural gas (LNG) technology and ionization imaging readout relies on the novel LAr LEM-TPC \textsuperscript{12}, operated in double phase with charge extraction and amplification in the vapor phase. The corresponding R&D programme (see e.g. Refs. \textsuperscript{13, 14}) is taking place at CERN and KEK (e.g. CERN RE18/ArDM \textsuperscript{15} is a small-scale 1 ton detector of the GLACIER-design, being commissioned at CERN; the LEM/THGEM are developed in Collaboration with RD51 \textsuperscript{16}). European and Japanese groups are collaborating towards the realization of very large 100 kton-scale detectors. The powerful imaging is expected to offer excellent conditions to reconstruct with high efficiency electron events in the GeV range and above, while considerably suppressing the neutral current background mostly consisting of misidentified \(\pi^0\)’s.

– **Non-segmented liquid Scintillator Detectors**: LENA is proposed as a 50 kton liquid scintillator tank of height 100 m and diameter of 26 m, surrounded by 2 m of water for vetoing external muons. The scintillation light produced is detected by 12’000 photomultipliers of 50 cm diameter each. Intensive R&D on liquid scintillators and photo-sensors has been carried out in the last years \textsuperscript{17}. BOREXINO \textsuperscript{18} is a large liquid scintillator detector presently operating at Gran Sasso. The capabilities to study and identify neutrino beams events is being addressed \textsuperscript{19}.

A comparison of the physics performance of the three detector options is planned within the WP4 of the LAGUNA design study. These simulations include the physics reach of long baseline experiments from neutrino beams from CERN.

\textsuperscript{1}The present versions of the interim reports are in the range of 100-200 pages per document. The public documents are available upon request.
4 Physics goals of next generation long baseline experiments

We can consider the following goals for next generation long baseline experiments beyond the current round of approved experiments:

1. Detect of the $\nu_\mu \rightarrow \nu_e$ in the appearance mode and measure $\theta_{13}$ or improve limit on $\theta_{13}$ by an order of magnitude compared to current reactors, T2K [20] and NOvA [21];
2. Measure the CP violation in the leptonic sector parametrized by $\delta_{CP}$;
3. Determine the neutrino mass hierarchy;
4. Detect of the $\nu_\mu \rightarrow \nu_\mu$ in the disappearance mode to reduce the experimental errors on $\Delta m_{32}^2$ and $\theta_{23}$ and observe the $\nu_\mu$ oscillation behavior (of the 1st and 2nd maximum);
5. Detect $\nu_\mu \rightarrow \nu_\tau$ in appearance mode with statistics significantly improved compared to OPERA [22];
6. Measure the “solar” product $\Delta m_{21}^2 \times \sin^2 \theta_{12}$ in the $\nu_\mu \rightarrow \nu_e$ appearance channel.

We postpone the discussion of the three last measurements, point 4 being limited by systematic errors. We however point out that they are as relevant as the first three.

The discovery of $\theta_{13}$ is determined by the ability to detect a statistically significant excess of $\nu_e$ charged current events above the predicted background, and its sensitivity scales therefore as $S/\sqrt{B}$. Hence, the next generation experiments require significantly more event rate and better background rejection compared to present round T2K and NOvA, and should aim to improve the $\theta_{13}$ statistical sensitivity by at least one order. A precise knowledge of the beam flux and neutrino cross-sections is also mandatory, to contain systematic errors – e.g. the $\nu_e$ contamination of conventional beam is on the order of 1% of $\nu_\mu$, hence a 10% systematic error is equivalent to a systematically limited sensitivity of $\sin^2 2\theta_{13} \approx O(1\%)$ on the appearance signal. The study of CP-violation is more challenging since it requires to measure the oscillation probability as a function of the neutrino energy, or alternatively to compare large samples of $\nu_e$ and $\bar{\nu}_e$ CC events, and suffers in general from neutrino oscillation parameters degeneracies.

To illustrate the case, we consider the T2K sensitivity $\sin^2 2\theta_{13} > 0.01$ (90% C.L.) obtained with 22.5 kton fiducial mass of Superkamiokande and 5 years of neutrino running at a proton beam power of 750 kW. If an excess is found in T2K, we can envisage a precise measurement of the $\nu_\mu \rightarrow \nu_e$ oscillation probability with an increase of beam intensity up to 1.66 MW ($\simeq \times 2$), a partial re-optimization of the flux within the constraints of an existing beamline infrastructure – longer baseline but smaller off-axis angle to Okinoshima island to increase beam energy ($\simeq \times 1$) – and a 100 kton liquid Argon TPC ($\simeq \times 4.5$) but higher detection efficiency ($\simeq \times 2$) and lesser background ($\simeq \div 2$) [23], for an overall gain of $(2 \times 4.5 \times 2)/\sqrt{2} \times 4.5/2 \approx 10$. See Ref. [24] for details.

Similar considerations apply to the US scenarios [25].

4.1 Measurement of the oscillation probability as a function of energy

The neutrino flavor oscillation probability including atmospheric, solar and interference terms, as well as matter effects, can expressed using the following equation [26–28]

$$P(\nu_e \rightarrow \nu_\mu) \sim \sin^2 2\theta_{13} \cdot T_1 + \alpha \cdot \sin \theta_{13} \cdot (T_2 + T_3) + \alpha^2 \cdot T_4.$$  \hspace{1cm} (1)

where,

$$T_1 = \sin^2 \theta_{23} \cdot \frac{\sin^2[(1 - A) \cdot \Delta]}{(1 - A)^2}$$

$$T_2 = \sin \delta_{CP} \cdot \sin 2\theta_{12} \cdot \sin 2\theta_{23} \cdot \sin \Delta \frac{\sin(A\Delta)}{A} \cdot \frac{\sin[(1 - A)\Delta]}{(1 - A)}$$

$$T_3 = \cos \delta_{CP} \cdot \sin 2\theta_{12} \cdot \sin 2\theta_{23} \cdot \cos \Delta \frac{\sin(A\Delta)}{A} \cdot \frac{\sin[(1 - A)\Delta]}{(1 - A)}$$
$$T_4 = \cos^2 \theta_{23} \cdot \sin^2 2\theta_{12} \frac{\sin^2 (A\Delta)}{A^2}.$$  

(2)

where \(\alpha \equiv \frac{\Delta m^2_{31}}{\Delta m^2_{21}}\), \(\Delta \equiv \frac{\Delta m^2_{31} L}{4E}\), \(A \equiv \frac{2\sqrt{2} G_F E_n}{\Delta m^2_{31}}\). \(\Delta m^2_{31} = m^2_3 - m^2_1\), \(\Delta m^2_{21} = m^2_2 - m^2_1\), \(\theta_{13}\) is the mixing angle of the 1st and 3rd generations, while \(\theta_{12}\) is that for 1st and 2nd, and \(\theta_{23}\) is that for 2nd and 3rd generations.

From the analysis of this expression, it can be noted that the effects of the CP phase \(\delta_{CP}\) appear as either [23]:

- a difference between \(\nu\) and \(\bar{\nu}\) behaviors which corresponds to the sign changes \(\delta_{CP} \rightarrow -\delta_{CP}\) and \(A \rightarrow -A\) (this method is sensitive to the \(CP\)-odd term \(T_2\) which vanishes for \(\delta_{CP} = 0\) or \(180^\circ\));
- a formal parametric dependence of the energy spectrum shape of the appearance oscillated \(\nu_e\) as given by the formula \(P(\nu_\mu \rightarrow \nu_e)\) as a function of \(\delta_{CP}\) and all other oscillation parameters (this method is sensitive to all the non-vanishing \(\delta_{CP}\) values including \(180^\circ\)).

The neutrino beam energy spectrum needs therefore to be tuned to measure the oscillatory pattern of the flavor conversion process on the e.g. 1st and 2nd maxima. Referring to Table 1, we note that for the shortest baseline CERN-Fréjus, the energy of the 1st maximum is \(\simeq 0.26\) GeV. It grows linearly with distance and reaches \(\simeq 4.65\) GeV for the longest baseline CERN-Pyhäsalmi. Given the \(L/E\) dependence of the flavor oscillation, the neutrino beam energy should scale with the chosen baseline \(L\) in order to cover those 1st and 2nd maxima.

As example, the probability of \(\nu_\mu \rightarrow \nu_e\) oscillation for \(\sin^2 2\theta_{13} = 0.01\) and different values of \(\delta_{CP}\) with and without matter effects is shown in Figure 1 for the CERN-Pyhäsalmi baseline. The plots illustrate qualitatively the fact that a measurement of the oscillation probability as a function of energy provides direct information on the \(\delta_{CP}\)-phase, since this latter introduces a well-defined energy dependence of the oscillation probability, which is different from the, say, energy dependence introduced by \(\theta_{13}\) alone (when \(\delta = 0\)). If the neutrino energy spectrum of the oscillated events is experimentally reconstructed with sufficiently good resolution in order to distinguish first and second maximum, useful information to extract the CP phase is obtained.

We note that the chance to measure both 1st and 2nd maxima increases with the baseline. Below few hundred MeV (e.g. \(\lesssim 400\) MeV) the vanishing cross-section and nuclear effects including Fermi motion limit the statistics and the energy resolution (for reconstructed neutrino energy). Hence we favor baselines in which both first and second maxima are above 400 MeV which implies \(L \gtrsim 600\) km and a first maximum above \(E \simeq 1\) GeV.

5 Prospects for high intensity neutrino beams from CERN

To first order of optimization, neutrino rates in conventional beams are proportional to the incident primary proton beam power [29], hence intense neutrino beams can be obtained by trading proton beam intensity with proton energy. So two basic approaches may be considered: a relatively low proton energy accompanied by high proton intensity or the second choice is higher proton energy with lower beam current. The problem at low energy is to obtain the high currents while the challenge at high energy is the acceleration power to quickly reach the highest energy while maintaining a short acceleration cycle.

To second order of optimization the primary proton energy can be tuned to produce the maximum yield of secondary pions relevant for the production of neutrinos of energy covering the first and second maximum of the oscillation.

We discuss these points with concrete examples.
Oscillation probability for $L = 2300$ km

**Fig. 1:** Probability of $\nu_\mu \rightarrow \nu_e$ oscillation for different values of $\delta_{cp}$ without and with matter effects for $\Delta m_{32}^2 > 0$ (NH). In this example, the CERN-Pyhäsalmi baseline and $\sin^2 2\theta_{13} = 0.01$ were chosen.

### 5.1 Upgraded CNGS

An intensity upgraded CNGS with a low energy focusing optimization [30] or a coupling to a large detector located at an appropriately chosen off-axis position would give improvements in $\theta_{13}$ reach [31, 32] compared to the current optimization for OPERA and ICARUS-T600, and sensitive searches for CP-violation and neutrino mass hierarchy determination could be possible [31]. These discussions rely on the observation that the CERN SPS has fewer protons and a slower cycle than JPARC or FNAL but could accelerate protons up to 400 GeV with a cycle of 6 s. Hence, the average beam powers on target are comparable.

An analysis of the maximum potential proton flux from the SPS including possible upgrade scenarios was consequently performed in Ref. [33]. We summarize those results below based on the following assumptions: 200 days per year of operation, 80% global machine efficiency and 85% sharing of the beam (i.e. LHC+neutrinos only). See Table 2:

- Based on operational experience, it can be estimated that dedicating the SPS FT time to neutrinos would yield a beam power of 500 kW and $9.4 \times 10^{19}$ pots/yr (factor 2 compared to the “nominal CNGS”).
- With a double batch injection in the PS from the PSB, one could envisage an acceleration of $7 \times 10^{13}$ protons in the SPS with a cycle of 7.2 s and a beam power of 600 kW. This would yield $11.4 \times 10^{19}$ pots/yr (factor 2.5 compared to the “nominal CNGS”).
Table 2: Expected pot per year \(10^{19}\) for different machine scenarios. \(E_{\text{tot}} \equiv E_p \times N_{\text{pot}}\) corresponds to the total amount of energy deposited on the target per year, which is a relevant quantity to estimate neutrino event rates.

| Machine param. | PS+SPS | SpS RF upgrade | SPL+SP2+SPS new RF | SPL + PS2 | New HP-PS | Booster + RCS 4 MW |
|----------------|--------|----------------|-------------------|-----------|-----------|-------------------|
| Proton energy \(E_p\) | 400 GeV | | | | | |
| \(N_{\text{pot}}/\text{yr} \times 10^{19}\) | 4.8 | 7 | 10 | 12.5 | 25 | 10 |
| \(T_e\) (s) | 6 | 7.2 | 4.8 | 2.4 | 1.2 | \((8.33\,\text{Hz})^{-1}\) |
| Beam power (MW) | 0.5 | 0.6 | 1.3 | 0.4 | 1.6 | 4 |
| Global efficiency | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 |
| Beam sharing | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 1.0 |
| Running (d/y) | 200 | 200 | 200 | 200 | 200 | 200 |
| \(E_{\text{tot}} \equiv E_p \times N_{\text{pot}}\) \((\times 10^{22}\,\text{GeV-pot/yr})\) | 4 \times 2 | 4.5 \times 2 | 10 \times 4 | 4 \times 2 | 15 \times 5 | 43 \times 16 |

With the planned new LHC injection chain (see Section 5.2), one could envisage accelerating \(10^{14}\) protons per SPS cycle. With a new SPS RF system these protons would be accelerated to 400 GeV every 4.8 s. This would yield a beam power of 1.3 MW and \(24.5 \times 10^{19}\) pots/yr (factor 5 compared to the “nominal CNGS”).

Beam losses and equipment heating in the various accelerators and beam lines will have to be controlled with careful machine tuning and improved controls.

These scenarios are very promising for the future in view of the increased proton fluxes able to be accelerated in the SPS. However, the bottleneck is the intensity limitation of the CNGS infrastructure which without action is essentially limited to \(4.5 \times 10^{19}\) pot/yr \([33]\). To increase the beam power of CNGS will require a radiation protection re-classification and/or partial reconstruction of its beam-line infrastructure, raising questions of feasibility, timescale and costs. At this stage, the solution to upgrade the CNGS intensity beyond a factor \(\times 2\) seems disfavored. Unfortunately it seems that potential upgrade scenarios were neglected during the design of the CNGS facility.

5.2 Plans for the SLHC injection line – LP-SPL + PS2

During the period 2008-2011, a new 160 MeV H- linac (Linac4) will be built to replace the present 50 MeV proton linac (Linac2). This is the first phase of a plan to renew the LHC injector complex and significantly improve its characteristics \([34]\). In a second phase, it was proposed to replace the present 26 GeV PS and its set of injectors (Linac2 + PSB) by a \(\sim 4\) GeV superconducting proton linac (SPL) followed by a \(\sim 50\) GeV synchrotron (PS2). The SPS itself will be upgraded for injection at 50 GeV and for better performance with high brightness beams.

Beyond the advantages for the LHC luminosity, an order of magnitude higher proton flux at 50 and 4 GeV and a new range of possibilities will be available for other users. The current SPS-based CNGS programme could significantly profit, as discussed in the previous section, but the maximum permissible beam intensity onto the CNGS target is limited by the design of its infrastructure and related radiation safety issues.

With the LP-SPL+PS2 parameters and the upgrade in the SPS intensity, we can conclude the following:

- The LP-SPL+PS2 and a new SPS RF system could accelerate protons to 400 GeV with a cycle of
4.8 s. This would yield a beam power of 1.3 MW and \(24.5 \times 10^{19}\) pots/yr (factor 4 compared to the “nominal CNGS”).

In conclusion, the LP-SPL and PS2 coupled to a new neutrino target and focusing region designed for high power followed by a new decay tunnel directed towards a LAGUNA site (in the following tentatively called CNXX) could be used to fully exploit the 400 GeV protons 1.3 MW power from the SPS.

5.3 A high power PS (=HP-PS) or actually HP-PS2?

As discussed previously, the required neutrino beam energy should cover the range \([0, 7]\) GeV to explore the oscillatory behavior of the flavor conversion in the various baseline configurations. Given the decay kinematics, the relevant parent pions have an energy in the range \([0, 15]\) GeV. This does not require 400 GeV protons and an energy of 50 GeV is sufficient to kinematically produce mesons of the relevant energies.

Actually 50 GeV protons produce a neutrino spectrum with less tail at high energy than 400 GeV protons. This is an advantage when considering backgrounds from neutral current interactions in the far detectors.

We can hence argue that:

- The baseline FT parameters defined by the PS2 working group \([35]\) yield \(1.2 \times 10^{14}\) protons at 50 GeV with a cycle of 2.4 s. This would correspond to a beam power of 0.4 MW and \(7.7 \times 10^{20}\) pots/yr. In terms of \(E_{\text{tot}} \equiv E_p \times N_{\text{pot}}\) this gives a factor of 2 compared to the “nominal CNGS”. There is therefore almost no gain compared to the optimized PS+SPS scenario, although the benefit of relieving the present SPS from demanding high intensities could be an advantageous choice for the long term operation for the LHC.

- A high power PS2 (=HP-PS2), whereby a factor 4 in intensity compared to the baseline parameters is assumed, could be achieved by doubling the proton intensity and doubling the repetition rate. This would yield a beam power of 1.6 MW and \(3 \times 10^{21}\) pots/yr. In terms of \(E_{\text{tot}} \equiv E_p \times N_{\text{pot}}\) this corresponds to a factor 5 compared to the “nominal CNGS”.

The possibility to change the design of the PS2 to power upgrade necessitates a dedicated critical study: is it necessary to consider an increase of the machine aperture (with impact on magnets, etc.)? Could a higher injection energy be envisaged to reduce space charge at injection? A certain fraction of the desired intensity increase could be obtained by “operational experience”: which fraction? The increase of the repetition rate would imply an upgrade of the magnet power supplies and of the RF system, which could be implemented later. Is there sufficient space reserved for the accelerating regions? All these questions need careful answers but ultimately there does not seem to be any technical show-stopper. Operational experience, e.g. at the J-PARC MR, will in the coming years certainly provide very valuable information.

5.4 High energy rapid cycling synchrotrons?

The LP-SPL+PS2 design was proposed as presenting significant advantages in the CERN context, especially because of its flexibility and its capability to evolve towards the very large beam power. On the other hand, rapid cycling synchrotrons (RCS) are being developed as an alternative solution to reach high power at high energy and were featured in proposals from Brookhaven and RAL (see e.g. \([36]\)). JPARC is presently commissioning a 25 Hz 3 GeV RCS as injector to the 30 GeV Main Ring \([24]\). There is no doubt that a 8 Hz 30 GeV proton RCS with a power of 4 MW as discussed previously in the CERN context \([37]\) would provide “ultimate” superbeam performance for long baseline experiments and could be used as the proton driver of the neutrino factory. This might well be the correct path for high power at
CERN. However, in the following, we will focus on the physics performance of a 1.6 MW HP-PS2. A 4 MW proton source would reduce the running time of the experiment accordingly.

6 Expected neutrino oscillation physics performance of a European long baseline experiment based on a CERN 1.6 MW HP-PS2 superbeam

Based on the previous arguments, we now discuss the expected physics performance of long baseline neutrino physics based on a 1.6 MW HP-PS2 based at CERN. Our focus is on $\theta_{13}$ determination, CP-violation discovery and neutrino mass hierarchy determination.

In order to have a preliminary quantified assessment of the physics performance, a GEANT4-based [38] simulation was developed in order to compare the meson yields in proton interactions of 5, 30, 50 and 400 GeV incident energy. A graphite target was chosen since it is widely used in current experiments. It has a density of $\rho = 2.2 \text{ g/cm}^3$, a diameter of 4 mm and a length of 100 cm. The power dissipation in the target was not addressed. The standard GEANT4 reference physics model (QGSP_BERT 3.3) has been used, in absence of a better choice. Secondary mesons produced in the interactions crossing a 1 m$^2$ area behind the end of the target were recorded during the simulation and used for computation of the neutrino flux. In order to compare the proton energy options, the secondary meson production yield was normalized by the incident proton energy $E_p$. The resulting yields $Y/E_p$ in particles/GeV$^2$/proton are shown in Figure 2(left). For secondary meson energies below 5 GeV the energy scaling law is rather remarkable since the 5, 30 and 50 GeV curves almost overlap. At higher energies the tail increases as the incident proton energy increases. At 400 GeV the tail extends very high above the relevant secondary pion range defined as [0,15] GeV. It is also evident that 400 GeV produce less low energy secondaries per proton than at lower proton energies. In this sense, the SPS energy is not optimized as it produces several very high energy pions. We will attempt to recover this situation by considering an off-axis position.

We initially computed the neutrino fluxes assuming ideal focusing. In this case, all secondaries reaching the 1 m$^2$ area behind the target were ideally focused and then decayed to produce neutrinos. Ideal focusing implies that their 3-momentum was rotated around the meson position in the transverse plane till their transverse momentum vanishes and the decay path was ignored. The ideal focusing calculation is an important method to optimize the proton incident energy by maximizing the yield of secondaries in the relevant energy. One can subsequently design a focusing system to best match the ideal conditions. In our simulation, the neutrinos crossing a 100 m$^2$ area detector placed at an arbitrary distance of 1000 km is used to compute the resulting flux. The flux are also normalized to the incident proton energy in order to easily compare the 5, 30, 50 and 400 GeV incident proton curves. These normalized neutrino fluxes $\phi_{\nu}/E_p$ are plotted in Figure 2(right). The vertical arrows indicate the energy of the 1st maxima of the neutrino oscillations for the 7 different baselines considered in LAGUNA.

We conclude from these plots that the 30 and 50 GeV incident proton energies are the most adequate to produce a wide band neutrino beam neutrino with the desired energy coverage.

We then use the NUX$^2$ cross-sections in order to compute the $\nu_\mu$ CC event rate and their energy distribution (in absence of neutrino oscillations). The results are shown in Figure 3(left). The 30 and 50 GeV protons produce the best results, while the beam produced by 400 GeV protons is too hard.

In order to compensate for this problem, we can consider the “off-axis” technique, pioneered in the Brookhaven neutrino oscillation experiment proposal [39] and used in T2K and NOvA, which consists of placing a neutrino detector at some angle with respect to the conventional neutrino beam. An “off-axis” detector records approximately the same flux of low energy neutrinos, as the one positioned “on-axis”, originating from the decays of low energy mesons. In addition, though, an “off-axis” detector records

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2The NUX neutrino-nucleon interaction code was developed to produce neutrino-nucleus interactions, including quasi-elastic, resonance production and deep inelastic scattering. The combined FLUKA(PEANUT)+NUX model gave outstanding results when compared with NOMAD data.
an additional contribution of low energy neutrinos from the decay of higher energy parents decaying at a finite angle.

The effect of an 0.25° off-axis configuration is illustrated in Figure 3(right), where the vertical axis has the same scale as for the on-axis configuration (same Figure (left)). We can see that a small off-axis angle is very effective at suppressing high-energy neutrinos. This method maintains the flux relatively unchanged and a broad neutrino spectrum is obtained, quite convenient for optimally measuring the first and second oscillation maxima.

Similar conclusions as for the on-axis apply here although the off-axis angle is effective at rescuing the 400 GeV SPS case. This can be a good solution to allow the same new beam-line to operate initially with the (existing) SPS until the HP-PS2 is commissioned. Indeed, the present foreseen localization of the PS2 ring, its extractions lines and the possible associated experimental areas [40] should make it conceivable to extract via appropriate transfer lines both PS2 and SPS beams into the new CNXX beam target area, in particular if the target and the decay tunnel are oriented towards a north-European far location.

7 Physics performance with a realistic horn focusing

In order to assess the physics performance based on the HP-PS2 with a realistic – although not fully optimized geometry – horn focusing system, we implemented a magnetic focusing system in our simulation, with similar geometry as that of the NUMI beamline [41], choosing as a starting point the NUMI-ME configuration. At this stage, we concentrate on three baselines CERN-Sierozsowice (950 km), CERN-Slanic (1544 km) and CERN-Pyhäsalmi (2300 km). Results for the other baselines will be reported later.

A fast particle tracking programme which neglects interactions of secondaries in the focusing and other beam line materials, has been used to rapidly estimate the neutrino fluxes and integrate them to compute the expected event rates. These latter are summarized in Table 3 in case of no flavor oscillations.
Fig. 3: (left) Normalized energy spectrum of beam muon neutrino charged current interactions in absence of neutrino oscillations $\nu_\mu$ CC/E; (right) same for an off-axis 0.25° configuration.

The figures are calculated for the NUMI-ME-like realistic focusing, normalized for one year and a liquid Argon detector with a mass of 100 kton.

The CERN-Slanic (1544 km) and CERN-Pyhäsalmi (2300 km) were envisioned with an off-axis angle of 0.25° while the CERN-Sierozsowice (950 km) has twice the off-axis angle 0.5° in order to a neutrino beam spectrum of lower energy given the shorter distance.

The event rates are in the range of 10’000 to 20’000 neutrino events per year for a positive horn polarity (neutrino run) and about 1/3 antineutrino events (for 50 GeV) to about 1/2 antineutrino events (for 400 GeV) for the opposite polarity of the horn (antineutrino run), assuming the same number of pots for each polarity. One a priori advantage of the high energy is the relatively symmetric production of positively and negatively charged pions. While at 50 GeV, leading charge effects in the fragmentation leads to an excess of $\pi^+ \rightarrow \nu's$ compared to $\pi^- \rightarrow \bar{\nu}'s$. As a result, the rate of events in the antineutrino run is more suppressed for 50 GeV protons than for 400 GeV. However, the contamination of neutrino events in the antineutrino run ($\nu_\mu$ CC contamination relative to $\bar{\nu}_\mu$ CC in antineutrino run) is more favorable for 50 GeV protons than for 400 GeV because very forward meson production is a dominant source of wrong helicity neutrinos at high energy.

When computing oscillation sensitivities, we include for each run polarity, the opposite polarity particles which are not defocalized are included in the calculation and added to the rate since we neglect at this stage the experimental determination of the helicity of the incoming neutrino (or the charge of the outgoing lepton). Detailed oscillation sensitivity calculations (as those detailed below) show that the opposite neutrino helicity contamination plays a non-negligible role in the sensitivity to CP-violation. Hence, from that point of view, we favor 50 GeV protons over 400 GeV and from now on focus on this case.

The expected sensitivities were computed with the help of the GLOBES [42] software, in a similar way to what we did previously which assumed a 100 kton liquid Argon detector (see Ref. [31] for details):

- In order to discover a non-vanishing $\sin^2 2\theta_{13}$, the hypothesis $\sin^2 2\theta_{13} \equiv 0$ must be excluded at the given C.L. As input, a true non-vanishing value of $\sin^2 2\theta_{13}$ is chosen in the simulation and a
Table 3: Event rate calculated with a NUMI-ME-like realistic focusing, normalized for one year and a liquid Argon detector with a mass of 100 kton.

| Distance/OA | neutrino run | antineutrino run |
|-------------|--------------|------------------|
|             | $\nu_\mu$CC ($\overline{\nu}_\mu$CC) | $\nu_e$CC ($\overline{\nu}_e$CC) / ($\nu_\mu + \overline{\nu}_\mu$) | $\nu_\mu$CC ($\overline{\nu}_\mu$CC) | $\nu_e$CC ($\overline{\nu}_e$CC) / ($\nu_\mu + \overline{\nu}_\mu$) |
| 1544 km     | 12181 (939)  | 96 (16)          | 2469 (5125) | 37 (39)          | 1.0 % |
| 950 km      | 22167 (327)  | 165 (9)          | 1270 (6068) | 27 (43)          | 1.0 % |
| 1544 km     | 23600 (333)  | 160 (7)          | 1267 (6467) | 20 (40)          | 0.8 % |
| 2300 km     | 10667 (153)  | 73 (3)           | 573 (2933)  | 7 (20)           | 0.8 % |

fit with $\sin^2 2\theta_{13} = 0$ is performed, yielding the “discovery” potential. This procedure is repeated for every point in the ($\sin^2 2\theta_{13}$, $\delta_{CP}$) plane. The corresponding sensitivity to discover $\theta_{13}$ in the true ($\sin^2 2\theta_{13}$, $\delta_{CP}$) plane at 3$\sigma$ is shown in Figure 4. The (left) panel shows the sensitivity with $3 \times 10^{21}$ pot/year and 5 years of neutrino run; the (right) panel assumes 5 years of neutrino run plus 5 years of anti neutrino run. $\implies$ The $\theta_{13}$ sensitivity is in first approximation independent of the baseline since the decrease in flux with increasing squared distance is compensated by the increased neutrino cross-section with energy.

– By definition, the CP-violation in the lepton sector can be said to be discovered if the CP-conserving values, $\delta_{CP} = 0$ and $\delta_{CP} = \pi$, can be excluded at a given C.L. The reach for discovering CP-violation is computed choosing a “true” value for $\delta_{CP}$ ($\neq 0$) as input at different true values of $\sin^2 2\theta_{13}$ in the ($\sin^2 2\theta_{13}$, $\delta_{CP}$)-plane, and for each point of the plane calculating the corresponding event rates expected in the experiment. This data is then fitted with the two CP-conserving values $\delta_{CP} = 0$ and $\delta_{CP} = \pi$, leaving all other parameters free (including $\sin^2 2\theta_{13}$ !). The opposite mass hierarchy is also fitted and the minimum of all cases is taken as final $\chi^2$. The corresponding sensitivity to discover CP-violation in the true ($\sin^2 2\theta_{13}$, $\delta_{CP}$) plane is shown in Figure 5(left). At the shorter baseline, matter effects are at the level of 30 %, hence it can be difficult to detect and untangle this effect from CP-phase induced asymmetries. Indeed, for certain combinations of true $\sin^2 2\theta_{13}$ and $\delta_{CP}$, it is possible to fit the data with the wrong mass hierarchy and a rotated $\delta_{CP}$ by 90°, an effect labelled as $\pi$-transit [43]. $\implies$ The ability to discover CP-violation improves with the baseline, in particular as we approach the “magical” distance of Ref. [44] as in the case of the CERN-Pyhäsalmi baseline.

– In order to determine the mass hierarchy to a given C.L., the opposite mass hierarchy must be excluded. A point in parameter space with normal hierarchy is therefore chosen as true value and the solution with the smallest $\chi^2$ value with inverted hierarchy has to be determined by global minimization of the $\chi^2$ function leaving all oscillation parameters free within their priors. The sensitivity to exclude inverted mass hierarchy in the true ($\sin^2 2\theta_{13}$, $\delta_{CP}$) plane is shown in Figure 5(right). $\implies$ As expected, the sensitivity to the neutrino mass hierarchy improves with the baseline.
**Fig. 4:** (left) Discovery potential at $3\sigma$ for $\theta_{13}$, for CNXX (NUMI-ME-like Horns 50 GeV HP-PS2 protons) beam for three LAGUNA locations, $3 \times 10^{21}$ pot/year and 5 years of neutrino run; (right) same but with 5 years of neutrino run plus 5 years of anti-neutrino run.

**Fig. 5:** (left) Discovery potential at $3\sigma$ for CP-violation, for CNXX (NUMI-ME-like Horns 50 GeV HP-PS2 protons) beam for three LAGUNA locations, $3 \times 10^{21}$ pot/year and 5 years of neutrino run plus 5 years of anti-neutrino run; (right) Mass hierarchy discrimination at $3\sigma$ for same beam conditions.

### 8 Conclusions

With the eminent startup of neutrino reactor experiments as well as T2K and NOvA, one cannot exclude that a positive $\theta_{13}$ signal will be found in the next few years. This would indeed mean that $\sin^2 2\theta_{13} \gtrsim 0.01$, a value compatible with the interpretation of solar and atmospheric neutrino data [45], the recent MINOS appearance analysis [46] and the latest SNO result [47]. A positive signal would certainly provide a tremendous boost to long-baseline neutrino physics, opening the prospects to detect CP-violation with superbeams. In case that no evidence for $\theta_{13}$ is found in the current round of experiments, it will be worth to continue the quest with more intense superbeams (=“hyperbeams”) than presently envisaged for T2K and NOvA, and with more massive far neutrino detectors, allowing to improve the $\theta_{13}$ sensitivity and proton lifetime by at least an order magnitude.

Neutrino factories and beta-beams certainly represent fantastic precision machines that the neutrino community should hope for, however until their R&D is successfully accomplished, conventional neutrino superbeams remain technically proven solutions which can be accurately costed and reliably implemented on a timescale of a decade, even in the multi-MW regime, offering concrete plans to move forward.
From the different available options for superbeams, high-energy and wide-band beams associated to the longest baselines provide the best opportunities to reach the experimental goals, in some cases avoiding the necessity of antineutrino runs. The optimal proton source energy lies in the range $30 \div 50 \text{ GeV}$.

Both KEK/JPARC and FNAL are considering upgrade paths for their ongoing neutrino programmes along the lines described here. The European programme could become attractive with the very long baselines not elsewhere accessible ($\gtrsim 1300 \text{ km}$), and because of the flexibility offered by designing a completely new beamline (target, optics, off-axis angle, etc.), naturally provided that the timescale does not exceed the $\sim 2025$ horizon.

We therefore believe that a CERN HP-PS2 proton source should be envisaged since it would represent the most time- and cost-effective way to establish forefront long baseline neutrino physics in Europe with prospects of discovering CP-violation in the leptonic sector.

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