Optimization of neutrino beams for underground sites in Europe

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Abstract. We present an optimization procedure for neutrino beams which could be produced at CERN and aimed to a set of seven possible underground sites in Europe with distances ranging from 130 km to 2300 km. Studies on the feasibility of a next generation very massive neutrino observatory have been performed for these sites in the context of the first phase of the LAGUNA design study. We consider specific scenarios for the proton driver (a high power proton driver at 4.5 GeV for the shortest baseline and a 50 GeV machine for longer baselines) and the far detector (a Water Cherenkov for the shortest baseline and a LAr TPC for longer baselines). The flux simulation profits of a full GEANT4 simulation. The optimization has been performed before the recent results on $\nu_e$ appearance by reactor and accelerator experiments and hence it is based on the maximization of the sensitivity on $\sin^2 2\theta_{13}$. Nevertheless the optimized fluxes have been widely used since their publication on the internet (2010). This work is therefore mainly intended as a documentation of the adopted method and at the same time an intermediate step towards future studies which will put the emphasis on the performances of beams for the study of $\delta_{CP}$.

PACS. 14.60.Pq Neutrino mass and mixing

1 Introduction

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, has been explored within the LAGUNA design study. In order of increasing distance from Geneva the considered sites have been Fréjus (France) at 130 km, Canfranc (Spain) at 630 km, Caso (Italy) at 665 km, Sierosówce (Poland) at 950 km, Boulby (United Kingdom) at 1050 km, Slănic (Romania) at 1570 km and Pyhäsalmi (Finland) at 2300 km.

When coupled to very intense neutrino beams from CERN, large detectors hosted in such an underground site, could measure with high precision the mixing angle $\theta_{13}$, and eventually determine the neutrino mass hierarchy and the existence of CP violation in the leptonic sector.

The oscillation probability of the $\nu_\mu \rightarrow \nu_e$ channel is shown as a function of the neutrino energy in Fig. 1 for the considered baselines. The energy of the first oscillation maximum spans a wide range of energies for the considered baselines ranging from 0.26 MeV at 130 km up to 4.65 GeV at 2300 km, the full sequence being \{0.26, 1.27, 1.34, 1.92, 2.12, 3.18, 4.65\} GeV.

This parameter is crucial for the optimization of the energy spectrum of the neutrino beam as it will be shown later. Neutrino spectra should cover the region where the oscillation effect is maximal with high statistics and low intrinsic contamination of $\nu_\mu$. The study of CP-violation 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. The possibility to have a broad beam covering the second oscillation maximum at lower energy is beneficial since it provides additional input useful to constraint the effects of mass hierarchy and the $\delta_{CP}$ phase and limits the impact of systematic errors on flux normalization by providing spectral information.

In this work we investigate two options for the proton driver: a high power superconducting proton linac at 4.5 GeV and a high power synchrotron at 50 GeV. Concerning the detector technology we consider a 440 kt Water Cherenkov for the 130 km baseline and the low energy proton driver and a 100 kt LAr Time Projection Chamber (LArTPC) at longer baselines with the high energy accelerator. Realistic designs have been proposed for these two detectors: the MEMPHYS and the GLACIER concepts. Previous studies on a high-energy super-beam and a low energy super-beam are available. The simulation of fluxes is based on the GEANT4 libraries and the optimization is performed separately for each one of the considered baselines. The guiding line of the optimization is the final achievable sensitivity on $\sin^2 2\theta_{13}$. Furthermore a direct comparison of a high-energy and low-energy super-beam based on different accelerator scenarios has been done using of a coherent set of simulation tools.
A summary of the assumed accelerator parameters is given in Tab. 1. For the far detector we concentrated on two designs:

- The MEMPHYS water Cherenkov detector is envisaged as consisting of 3 separate tanks of 65 m in diameter and 65 m height each (440 kt). 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. Based on the extensive experience of Super-Kamiokande, this technology is best suited for single Cherenkov ring events typically occurring at energies below 1 GeV.

- GLACIER is a scalable concept for single volume very large LAr TPC with a mass of 100 kt. The powerful imaging will allow 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.
3 Optimization of the focusing system

The optimization of the neutrino fluxes for the CERN-Fréjus baseline with a Cherenkov detector and a 4.5 GeV proton driver has been studied extensively in [11] so in the following we will take the optimized fluxes obtained in that work and focus on the optimization of the focusing system for longer baselines assuming a LAr far detector and a 50 GeV proton driver.

The focusing system is based on a pair of parabolic horns which we will denote as horn (upstream) and reflector (downstream) according to the current terminology. This schema is the same which is being used for the NuMI beam. The target is modelled as a 1 m long cylinder of graphite ($\rho = 1.85 \text{ g/cm}^3$) and a radius of 2 mm. Primary interaction in the target were simulated with GEANT4 QGSP hadronic package.

The optimization relies on a parametric model of the horn and reflector profiles. The horn radius as a function of the coordinate along the proton beam, $r(z)$, has been parametrized as shown in the first row of Tab.2 in the three $z$ domains $[0, z_1), [z_1, z_2), [z_2, z_3)$ which reduce to nine after requiring continuity at the points $z_1$ and $z_2$ ($a, b, c, d, a’, b’, c’, r, z_1, z_2, z_3$). The layout of a typical configuration is shown in Fig.2.

In addition to the parameters related to the shape of the horn and the reflector, additional degrees of freedom are: the distance between the horn and reflector ($\Delta HR$), the length and radius of the decay tunnel ($L_{\text{tun}}, r_{\text{tun}}$), the longitudinal position of the target ($z_{\text{tun}}$) and the currents circulating in the horn and the reflector ($i_H, i_R$).

Following the approach already used in [11] for the optimization of the SPL-Fréjus Super Beam, we introduce, as a figure of merit of the focusing, a quantity $\lambda$ defined as the $\delta_{CP}$-averaged 99 % C.L. sensitivity limit on $\sin^2(2\theta_{13})$ ($:=\lambda_{99}(\delta_{CP})$) in $10^{-3}$ units

$$
\lambda = \frac{10^3}{2\pi} \int_0^{2\pi} \lambda_{99}(\delta_{CP}) \, d\delta_{CP}
$$

In the following we will denote the quantity $\lambda$ evaluated for a specific baseline $L$ as $\lambda_L$. A sample of $10^5$ secondary meson tracks per configuration was used. Fluxes were calculated with 20 energy bins from 0 to 10 GeV. The statistical fluctuations introduced by the size of the sample have been estimated by repeating the simulation for the same configuration several times with independent initialization of the GEANT4 random number engine. The spread is enhanced by the presence of single events which can be assigned large weights. The spread on the parameters $\lambda_L$ is of the order of 3-4%. The sensitivity limit was calculated with the GLoBES software [15] fixing a null value for $\theta_{13}$ and fitting the simulated data with finite values of $\sin^2 2\theta_{13}$ and $\delta_{CP}$ sampled in a grid of $10 \times 200$ points in the $(\delta_{CP}, \sin^2 2\theta_{13})$ plane for $\delta_{CP} \in [0, 2\pi]$ and $\sin^2 2\theta_{13} \in [10^{-2}, 10^{-4}]$. The 99% C.L. limit was set at the values corresponding to a $\Delta \chi^2$ of 9.21 (2 d.o.f.).

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In the simulation of the GLACIER detector the considered backgrounds are the intrinsic $\nu_e$ and $\bar{\nu}_e$ components of the beam. Reconstructed neutrino energy was divided into 100 MeV bins while the true neutrino energy in 40 MeV bins from 0 to 1.6 GeV. Four migration matrices for $\nu_e, \bar{\nu}_e, \nu_{\mu}$ and $\bar{\nu}_\mu$ are applied to signal events as well as backgrounds. The considered backgrounds are $\nu_{\mu}^{CC}$ interactions misidentified as $\nu_e^{CC}$, neutral current events and $\nu_e + \nu_{\mu}$ intrinsic components of the beam.

We followed two strategies in the optimization procedure which we will describe in the following subsections.

| $r(z)$ | $\sqrt{\frac{x^2}{a^2} - c}$ | $d$ | $\sqrt{\frac{x^2}{a'^2} - c'}$ |
|--------|-----------------|-----|-----------------|
| $z$ range | $[0, z_1)$ | $[z_1, z_2)$ | $[z_2, z_3)$ |
| Par. horn refl. | Par. horn refl. |
| $a$ | $85.5$ | $100$ | $d$ | $0.9$ | $3.9$ |
| $b$ | $7.0$ | $10.35$ | $r$ | $15$ | $40$ |
| $c$ | $0.2$ | $0.3$ | $z_1$ | $80$ | $97.6$ |
| $a'$ | $82.2$ | $100$ | $z_2$ | $83.0$ | $104.8$ |
| $b'$ | $2.18$ | $0.27$ | $z_3$ | $300$ | $300$ |
| $c'$ | $0.2$ | $0.3$ | |

Table 2: Analytic parametrization of the horn/reflecter radial profile $r(z)$ and central values of the parameters expressed in cm. $r$ is the conductor outer radius.
In a first step we decided to fix the horn and reflector shapes (central values of Tab. 2), the tunnel geometry ($L_{tun} = 300$ m, $r_{tun} = 1.5$ m) and the circulating currents (200 kA). We then varied the relative positions of the horn, the reflector and the target. We define the distance between the center of the target and the most upstream point of the horn as $z_{tar}$ while we indicate with $\Delta_{HR}$ the horn-reflector distance. After having chosen the best point in this space we did a similar exercise in the decay tunnel parameter space ($L_{tun}, r_{tun}$). At first order these two couples of parameters are expected to be weakly correlated so that doing the optimization in one pair of variables after fixing a specific choice for the other pair should not have a big impact on the final result.

The variables ($\Delta_{HR}, z_{tar}$) were sampled uniformly in the intervals $[0, 300]$ m and $[-1.5, 2.5]$ m respectively. Optimal values were then chosen for each baseline. In general a marked dependence of $\lambda$ on the longitudinal position of the target ($z_{tar}$) is observed while variations of $\Delta_{HR}$ have a reduced impact. In Fig. 3 we show, taking as an example, the dependence of $\lambda_{630}$ on $z_{tar}$ after marginalizing on $\Delta_{HR}$. For the 630 km baseline the optimal $z_{tar}$ lies around $+0.5$ m, while for $\Delta_{HR}$ a value of 50 m was chosen. At this stage of the optimization the best values for $\lambda_{630}$ cluster between 1.4-1.5. The first two columns of Tab. 3.1 give the $\Delta_{HR}$ and $z_{tar}$ pairs providing the best limit for each baseline ($\lambda_{min}, 3^{rd}$ column).

After having fixed $\Delta_{HR}, z_{tar}$ to the optimal values of Tab. 3.1 the tunnel length $L_{tun}$, previously fixed at 300 m, was sampled uniformly between $[10, 500]$ m keeping $r_{tun}$ fixed at 1.5 m. The optimized values for $L_{tun}$ are given in Tab. 3.1 (4$^{th}$ column). In the case of $L = 630$ km a gain of order 20% is visible in Fig. 4 (left) decreasing $L_{tun}$ from a 300 to 75 m.

The $r_{tun}$ was then sampled in $[0, 3]$ m having fixed the optimal tunnel length. The right plot of Fig. 4 shows that an improvement is obtained increasing $r_{tun}$ to 2 m. The optimized values for $r_{tun}$ are shown in Tab. 3.1 (5$^{th}$ column). The values of $\lambda$ obtained after the tunnel optimization ($\lambda_{min}$) are shown in the 6$^{th}$ column of Tab. 3.1. The variation between $\lambda_{min}$ and $\lambda_{min}'$ shows that the tunnel optimization is particularly effective for the short baselines for which the initial geometry was not appropriate.
for $z_{tar}$ which exhibits a strong correlation with $\lambda$. It is clear that putting the target more and more upstream with respect to the horn, is mandatory to get good exclusion limits, as far as the baseline increases.

The correlation between the longitudinal position of the target with respect to the horn and the mean energy of the $\nu_\mu$ spectrum ($\langle E_{\nu_\mu} \rangle$) is shown in Fig. 5. Putting the target upstream, high energy pions, which are typically produced at small angles, are preferentially focused resulting in a high energy neutrino spectrum.

The correlation between $\langle E_{\nu_\mu} \rangle$ and $\lambda$ is shown in Fig. 6. In general the optimal energies tend to roughly follow the position of the first oscillation maximum (red vertical lines in the plots). Mean energies below 2 GeV are difficult to get with a 50 GeV proton beam. A possible solution, which has not be considered in this work, could be to go towards an off axis beam for baselines lower than 600 km. The horizontal blue lines show the lowest values for $\lambda$ obtained with the previous fixed horn shape search.

The achieved performance is not drastically improved by the general search though some gain appears for $L > 1000$ km. Blue markers highlight the configuration providing the best limit for each baseline. It turns out that the same configuration provides the best limit both for 630 and 665 km and the same happens for 950-1050 and 1570 km. Given the limited improvement, we decided to stick with the best candidates obtained with the fixed horn shape search. This choice is also motivated by the fact that choosing the configurations with the minimum $\lambda$ has the disadvantage of being sensitive to statistical fluctuations.

### 4 Optimized fluxes

The $\nu_\mu$ fluxes obtained with the optimized focusing setups according to the fixed shape search are shown in Fig. 7 at a reference distance of 100 km. Fluxes are publicly available on the internet [4]. The flux increase as the mean energy increases can be intuitively explained considering that high energy pions are easier to focus since they naturally tend to emerge from the target in the forward direction and the neutrinos they produce have a higher chance to be in the far detector solid angle also thanks to the effect of the Lorentz boost. Un-osciliated interaction rates are given in Tab. 5. It can be noted that considerable samples of $\tau$ events becomes collectable with the fluxes optimized for the longer baselines.

### 5 Conclusions

As it was shown in [4], using the fluxes optimized with the procedure described above, the “discovery potential”

| Parameter | Interval          | Parameter | Interval     |
|-----------|------------------|-----------|--------------|
| $L_{tun}$ | [200, 1000] m    | $r_{tun}$ | 2 min        |
| $r_{tun}$ | [0, 8.2] m       | $\Delta_{HR}$ | 4300 m     |
| $z_{tun}$ | [-2.5, 1.5] m    | $i_H$, $i_R$ | [150, 300] kA |

Table 3. Fixed horn shape search. Optimal values for $\Delta_{HR}$, $z_{tun}$, $L_{tun}$ and $r_{tun}$.

Table 4. Focusing system parameters not related to the horn-reflector shapes.

![Fig. 5. Correlation between the longitudinal position of the target with respect to the horn and $\langle E_{\nu_\mu} \rangle$.](image)

![Fig. 6. Correlation between the figure of merit $\lambda$ and $\langle E_{\nu_\mu} \rangle$ (positive focusing).](image)
for $\theta_{13}$ turned out to be, at first order, almost independent of the baseline. Performances of high- and low-energy super-beams are comparable if we assume for both a 5% systematic error on the fluxes. Concerning the high-energy super beam, better results are obtained for intermediate baselines from 950 to 1570 km even though the difference is not marked. This merit factor, despite being obsolete in order of increasing baseline.

This result could be achieved by a systematic tuning of a few basic parameters of the focusing system: the horn-reflector distance, the target position and decay tunnel geometry.

An exhaustive discussion of the physics potential in terms of CP violation and mass hierarchy obtainable with the fluxes whose optimization is described in this work, has been recently developed in [10, 12, 13, 14, 15] and [20].

By adopting a suitable re-definition of the figure of merit, the approach followed in this study could in the future be specialised to the need for optimal sensitivity on the CP violating effects under the light of the recent measurement of $\theta_{13}$.

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### Table 5.

| $(\text{km})$ | $\nu_\mu$ (p.o.t. $\times 10^5$) | $\nu_\tau$ (p.o.t. $\times 10^5$) | $\nu_e$ (p.o.t. $\times 10^5$) | $\nu_\mu$ (p.o.t. $\times 10^5$) | $\nu_\tau$ (p.o.t. $\times 10^5$) | $\nu_e$ (p.o.t. $\times 10^5$) |
|-----------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 130 | 41316 | 174 | 0.42 | 5915 | 15 | 0.42 |
| 630 | 36844 | 486 | 28 | 1.5 | 13652 | 157 | 11 |
| 665 | 38815 | 516 | 28 | 1.5 | 14287 | 158 | 11 |
| 950 | 37844 | 349 | 40 | 1.0 | 14700 | 107 | 15 |
| 1050 | 51787 | 314 | 148 | 0.64 | 21728 | 88 | 65 |
| 1570 | 26785 | 174 | 170 | 0.67 | 11184 | 47 | 73 |
| 2300 | 17257 | 110 | 377 | 0.67 | 7577 | 32 | 172 |

Fig. 7. Neutrino fluxes at 100 km for the systems optimized with the fixed horn shape search. The energies of the oscillation maximum for each baseline (Fig. 1) are indicated with vertical lines having the same color as the corresponding spectrum. The integral fluxes in units of $10^{22} \nu_\mu/100 \text{ m}^2/\text{year}$ are 0.38, 1.59, 1.81, 2.69, 3.56, 3.93 and 4.48 in order of increasing baseline.