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The European Spallation Source Neutrino Super Beam for CP Violation discovery

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The discovery mainly by reactor experiments that the last mixing angle θ_{13} was relatively large, opened the door to the observation of a possible CP violation in the leptonic sector using conventional accelerator techniques with enhanced beam intensity. The already proposed projects had to re-optimise their parameters to take into account this new neutrino oscillation landscape. The first $\nu_\mu \rightarrow \nu_e$ oscillation maximum is better placed to observe CP violation for small θ_{13} values, but, for the measured value the second oscillation maximum is more sensitive and less affected by systematic errors. To operate a neutrino facility at the second oscillation maximum significantly more intense neutrino beams are needed than for the first one. The ESSνSB project proposes to use the world's most intense proton linac of the European Spallation Source under construction at Lund, Sweden. This new facility will provide a 5 MW/2 GeV proton beam by 2023. ESSνSB will exclusively operate on the second oscillation maximum covering at 5 σ statistical significance more than 50% of the CP violation parameter δ_{CP}. This project proposes to use a megaton Water Cherenkov neutrino detector installed 1000 m underground in a mine at a distance of about 500 km from the neutrino source. This project has a rich astroparticle physics program and could also study the proton lifetime.

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1. Introduction

The measurement of the last neutrino mixing angle θ_{13} [1] allowed to better define the world neutrino oscillation roadmap. The relatively high value of θ_{13} showed that neutrino facilities based on conventional beams could, with high probability, observe for the first time a CP violation in the leptonic sector and resolve the problem of the neutrino mass hierarchy.

By that time, the already designed future neutrino facilities supposed to use significantly more intense neutrino beams than the existing ones, had to readjust their parameters to better take into account the new landscape. Indeed, all new facilities were designed to cover very low θ_{13} values exploiting the first oscillation maximum. It has been shown [2] that for large θ_{13} values as the observed one, going to the second oscillation maximum was inducing a better performance concerning an eventual CP violation discovery. This comes from the fact that, in the neutrino oscillation probability $\nu_\mu \to \nu_e$, the term carrying the CP violation parameter δ_{CP} dominates the “atmospheric" and “solar" terms at low θ_{13} values at the first oscillation maximum, while for large values this is only true when going to the second oscillation maximum. It is also shown in [3] that the neutrino/antineutrino asymmetry in the vacuum is approximately equal to $0.30 \sin\delta_{CP}$ at the first oscillation maximum, while for the second oscillation maximum this value becomes $0.75 \sin\delta_{CP}$. This clearly shows that experiments at the second oscillation maximum have significantly higher sensitivity to δ_{CP} than those placed at the first oscillation maximum. The drawback is that going at the second oscillation maximum necessitates either to increase the distance between the neutrino source and the detector or to lower the neutrino energy or both. In all cases this decreases the statistics because increasing the baseline decreases the solid angle seen by the far detector while decreasing the neutrino energy below ~ 1 GeV decreases rapidely the neutrino interaction cross–sections.

To exploite the second oscillation maximum capabilities very intense neutrino beams are needed. Such a neutrino beam could be obtained using the European Spallation Source (ESS) [4] proton linac under construction in Lund, Sweden. The ESS proton linac will start operation at full power (5 MW) and energy (2 GeV) for neutron production in 2023.

A relatively low energy neutrino Super Beam has been extensively studied by the FP7 Design Study EUROν [5, 6], which did a similar study based on the CERN Superconducting Proton Linac (SPL, 4.5 GeV protons, 4 MW) [7] Super Beam and the MEMPHYS [8, 9] large Water Cherenkov detector placed in the Fréjus tunnel located at the first neutrino oscillation maximum (130 km).

This ESS neutrino Super Beam (ESSνSB) [10] study uses all previous studies applied on the high power linac of the ESS at Lund in Sweden as proton driver and a MEMPHYS type detector located in a deep mine at somewhere between 300 to 600 km distance, near the second neutrino oscillation maximum.

2. Neutrino beam based on ESS linac

The construction of the whole ESS facility for neutron production has started in September 2014 and will finish in 2023. The first proton beam with low energy and intensity is already expected by 2019. The main characteristics of the ESS linac are given in Table 1.

The proton pulse length being 2.86 ms, too long for the neutrino facility, has to be reduced to few μs, acceptable to the hadron collector device (horn pulsed with a 350 kA current) used to produce the neutrino beam. For this reason, an accumulation ring ($\sim$400 m circumference) has to be added before sending the proton beam to the neutrino target station. The utilisation of this ring obliges the use of H^- in the linac instead of protons. Indeed, H^- ions are needed because of the difficulty to inject protons in the accumulator while a large amount of protons is already circulating in. The H^- ions would be stripped of their two electrons at the position where the linac beam enters the accumulator ring.

Fig. 1 shows schematically how the neutrino facility could be added to the neutron one. A near detector can be added in the already ESS allocated area to measure the unoscillated neutrino flux and also measure the relevant neutrino cross-sections.

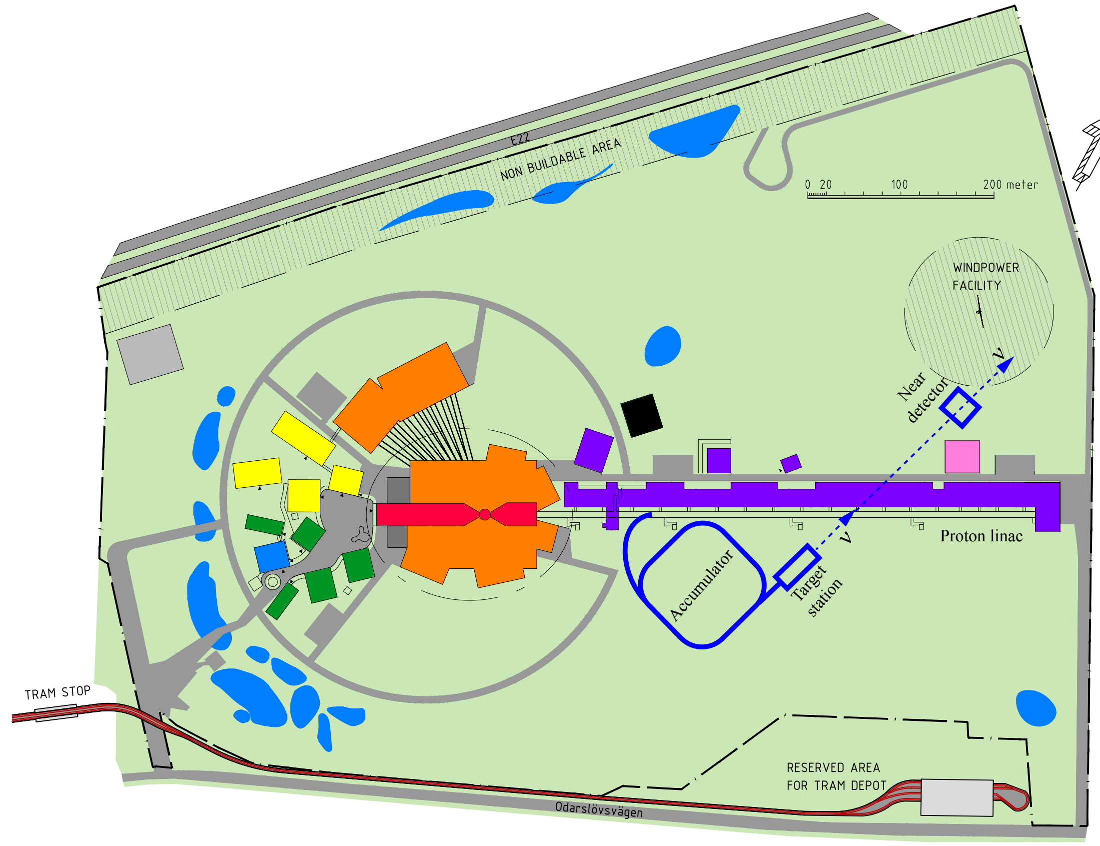

Figure 1: Layout of the ESS installations with a possible neutrino facility implementation. The extraction line from the linac, the accumulator, the target station (including the decay tunnel) and the near detector location are visible in dark blue.

The neutrino facility could be operated in parallel with the neutron one by doubling the linac repetition rate from 14 Hz to 28 Hz. Other operation modes are possible using other repetition rates but always with the aim to provide at the same time 5 MW protons to each facility. Indeed, for neutron production the linac duty cycle is only 4%. It could be raised to 8% for simultaneous

Table 1: Main ESS proton linac parameters.

Parameter	Value
Average beam power	5 MW
Proton kinetic energy	2.0 GeV
Average macro–pulse current	62.5 mA
Macro–pulse length	2.86 ms
Pulse repetition rate	14 Hz
Annual operating period	5000 h
Reliability	95%

operation for neutron and neutrino production. In order to increase the repetition rate and introduce H^-, some modifications of the proton linac are needed. This could also allow to increase the neutron brightness.

By sending the 2 GeV proton beam to a target as the one proposed by EUROν, the neutrino spectrum shown in Fig. 3 can be obtained for muon neutrinos and antineutrinos. In both cases, the mean neutrino energy is of the order of 400 MeV, well suited for a Water Cherenkov detector, but sitting in a region where the neutrino interaction cross–section is quite low.

In order to collect similar number of events for both, neutrino and antineutrino runs, ESSνSB proposes to operate the facility for 2 years in neutrino mode and 8 years in antineutrino mode. The annual operation period of the facility would be 5000 hours (208 days, 1.8×10^7 sec). More information about the beam and the target/horn station can be found in [11].

The obtained neutrino beam contains a 0.5% ν_e ($\bar{\nu}_e$) contamination in neutrino (antineutrino) mode. This small fraction of electron neutrinos, taking into account their absolute big number at the level of the near detector, can be used to measure the neutrino cross-sections at the relevant for this facility neutrino energies and thus reduce significantly the systematic errors. For this, a “smart” near detector is needed with a high rejection power of ν_μ events.

Fig. 3 presents the oscillated neutrino energy distribution for neutrinos detected at a distance of 540 km for $\delta_{CP} = 0$) for two years data taking in neutrino mode (about 200 events) and eight years in antineutrino mode (about 170 events). It is seen that the background is relatively low for both running modes, neutrinos and antineutrinos. The highest contamination ($\sim$13%) comes from the electron neutrinos contained in the primary neutrino beam. The second contamination is induced by the Neutral Current (NC) events ($\sim$5%).

3. CP violation at 2nd oscillation maximum

As explained in Section 1 the sensitivity to observe a CP violation at the second oscillation maximum is higher and less affected by systematic errors than at the first oscillation maximum. Taking advantage of the low neutrino energy beam and the very high intensity of the ESS proton beam, ESSνSB proposes to use this facility to go to the 2nd oscillation maximum.

In order to find the optimal distance where to place the far detector a study of the facility physics performance has been done. Although the initial ESS proton energy will be 2 GeV, empty

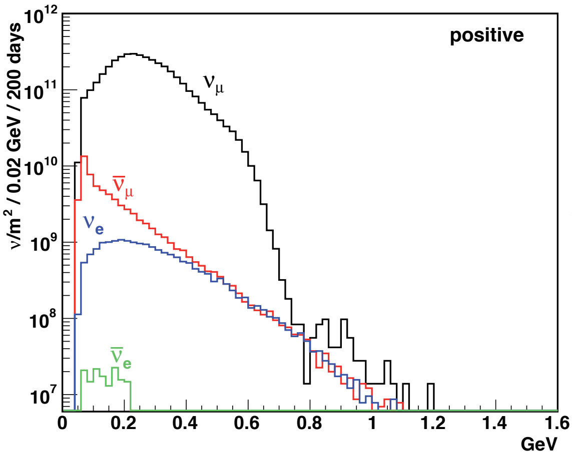

Figure 2: Neutrino energy distribution at a distance of 100 km on–axis from the target station, for 2.0 GeV protons and positive (left, neutrinos) and negative (right, antineutrinos) horn current polarities, respectively.

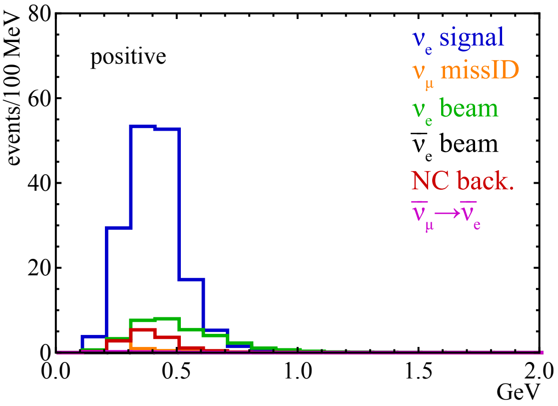

Figure 3: Energy distribution of the detected neutrinos and antineutrinos as reconstructed by MEMPHYS WC detector for two years of neutrino running (left) and eight years of antineutrino running (right) and a baseline of 540 km (2.0 GeV protons, $\delta_{CP} = 0$).

room inside the linac allows to go up to 3.5 GeV in future upgrades. Fig. 4 shows the obtained resolution on the CP parameter δ_{CP} versus δ_{CP} for several baselines. At $\delta_{CP} = 0^\circ$ and 180°, values to be excluded for CP violation discovery, $\Delta\delta_{CP}$ goes below 7°. From this Fig. it is shown that baselines higher than 600 km will give very large δ_{CP} uncertainties at values around $\pm 90^\circ$.

Fig. 5 presents the fraction of δ_{CP} covered versus the distance for several proton energies. It is seen that the best performance is obtained at a distance between 350 km to 600 km, depending on the proton energy, varied from 2 GeV to 3.5 GeV. Up to 60% of the δ_{CP} space can be covered with a 5 σ significance and up to 78% for 3 σ. For these studies it is assumed a 5% systematic error for the signal and 10% for the background. The very good performance comes again from the fact that this facility is almost exclusively operated on the second oscillation maximum.

Fig. 6 shows the $\nu_\mu \to \nu_e$ oscillation probability as a function of the neutrino energy on top

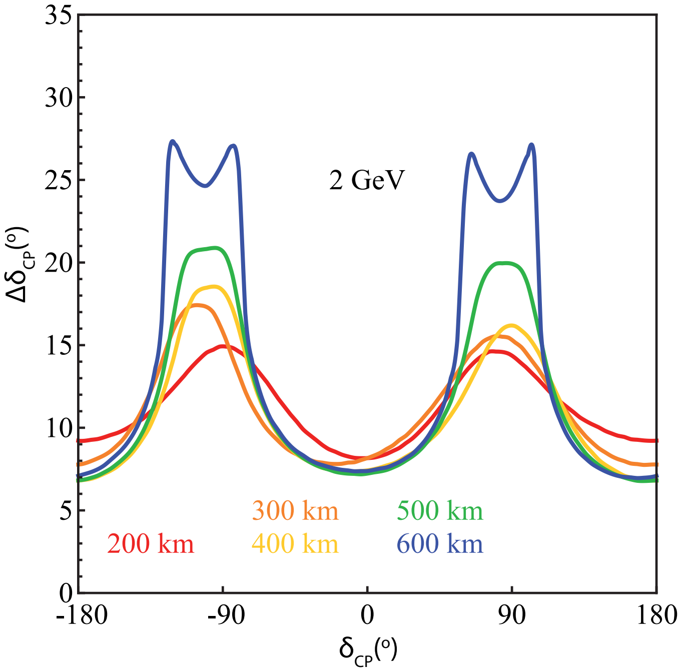

Figure 4: Precision on δ_{CP} versus δ_{CP} for several baselines and for 2 GeV protons.

of the unoscillated electron neutrino energy distribution for neutrinos detected by the megaton Cherenkov detector placed at 540 km. From this Fig. it is clearly seen how well the second oscillation maximum is covered.

A suitable far detector site has to be found in this distance range. As already mentioned, a Water Cherenkov (similar to MEMPHYS [8, 9]), performs very well for these neutrino energies. The fiducial volume of this detector is of the order of 500 kt. Two candidate mines in Sweden located at 360 km (Zinkgruvan) and 540 km (Garpenberg) could host this detector. This voluminous detector can also have a reach astroparticle physics program and proton lifetime measurements [12]. For a galactic supernova explosion it is expected to detect about 10^5 neutrinos providing valuable information on the explosion mechanism.

While the relatively short baseline limits the performance to determine the neutrino mass hierarchy, combining the “beam” neutrinos with the atmospheric ones could allow to have a 5 σ significance, if this problem is not meanwhile solved by other experiments. On the other side, the weak dependence on the mass hierarchy is an advantage for the CP violation discovery. Fig. 7 [13] presents the fraction of the full δ_{CP} range as function of the exposure. The width of the curves is induced by the unknown mass hierarchy. The details of the systematic errors considered can be found in [14]. On this same Fig. one can see that by doubling the exposure 72% coverage of δ_{CP} at 5 σ significance can be obtained while for 3 σ significance this coverage can go up to 85%.

4. Other physics subjects

Decreasing the proton pulse duration from 2.86 ms to a value around 1 μs can also significantly increase the neutron brightness [15]. In these conditions the massive neutron target can also be used

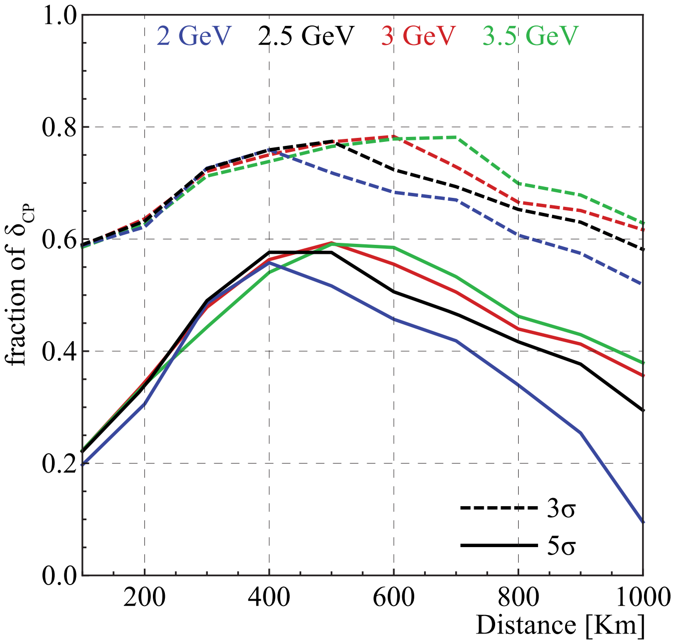

Figure 5: The fraction of the full δ_{CP} range as function of the baseline. The lower (upper) curve is for CP violation discovery at 5 σ (3 σ) significance.

for neutrino physics. Indeed, the pions produced will be stopped inside the target and decay at rest giving a muon and a 30 MeV mono–energetic muon neutrino. These neutrinos can be used in high precision neutrino experiments. Those produced by the decay of the muons (lifetime of 2.2 μs) can be used to measure the neutrino cross–sections in the region from 10 MeV to 50 MeV necessary to the supernova neutrino measurements [16].

At the level of the beam dump of the neutrino facility a huge number of muons can be collected for other applications. Fig. 8 presents the energy distribution of these muons. The mean energy is of the order of 0.46 MeV while, with an adequate collecting device, more than 4×10^{20} muons per year can be extracted. These muons can be used for a “low” nuSTORM neutrino experiments [17] and for R&D for 6D muon cooling for a possible future muon collider.

5. Conclusions

The ESSνSB project proposes to use the very powerful 5 MW/2 GeV proton linac of the European Spallation Source to produce a very intense neutrino beam with the aim to observe for the first time a possible CP violation in the leptonic sector.

This linac, under construction in Lund, will be ready by 2023, while the first low power and low energy beam is expected by 2019. During the construction of the ESS neutron facility it is taken particular care in order not to exclude any possibility to add on top of that the neutrino facility. The cost for upgrading the ESS linac to include the neutrino facility on top of the neutron one is significantly lower than building a new separate proton driver of similar power.

Enough space exists in the already allocated ESS area to add an accumulation ring, a neutrino target station and a near detector. The near detector could also measure the needed neutrino inter-

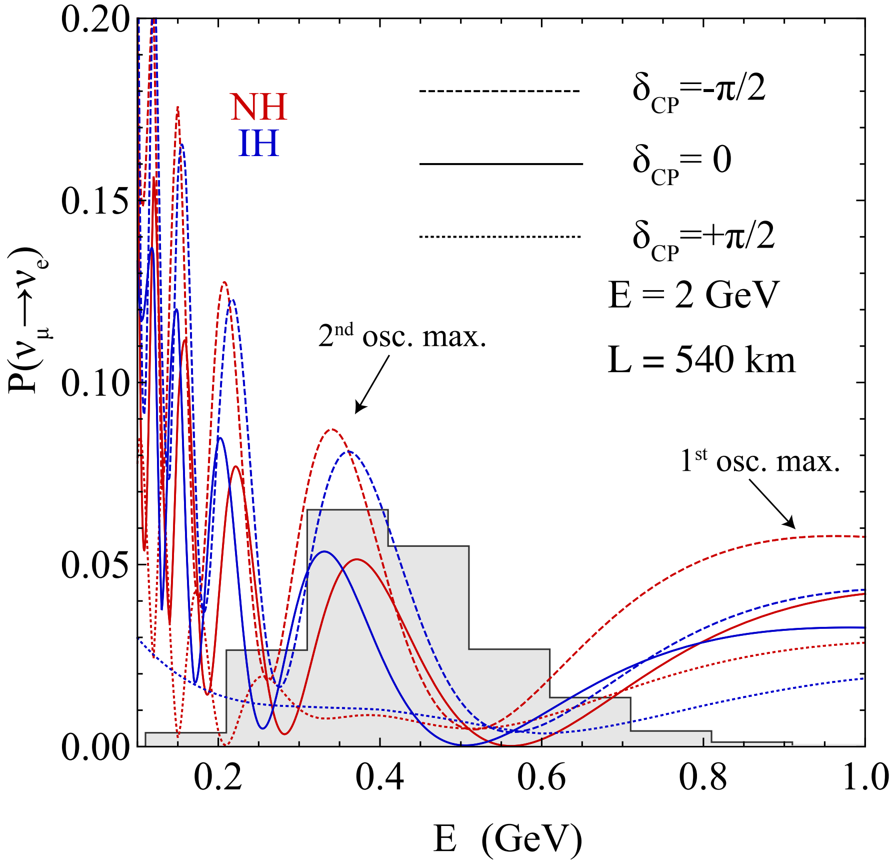

Figure 6: $\nu_\mu \to \nu_e$ oscillation probability as a function of the neutrino energy. The solid lines are for normal hierarchy (NH) while the dashed ones are for inverted hierarchy (IH). The shaded distribution is the energy distribution of electron neutrinos as they would be detected by MEMPHYS far detector.

action cross–sections. Two locations, corresponding to existing mines, have been found to host the far megaton Cherenkov detector, one at 360 km and the other one at 540 km from Lund. This large volume detector can also have a reach astroparticle physics program.

Using this neutrino facility, studies show that a δ_{CP} coverage up to 60% can be obtained, thanks to the fact that the facility can be operated at the second oscillation maximum, more sensitive to the neutrino/antineutrino asymmetry and less affected by the systematic errors.

This facility could be complementary to other long baseline facilities for CP violation observation operated at the first oscillation maximum using different detection technics as those based on the utilisation of liquid argon.

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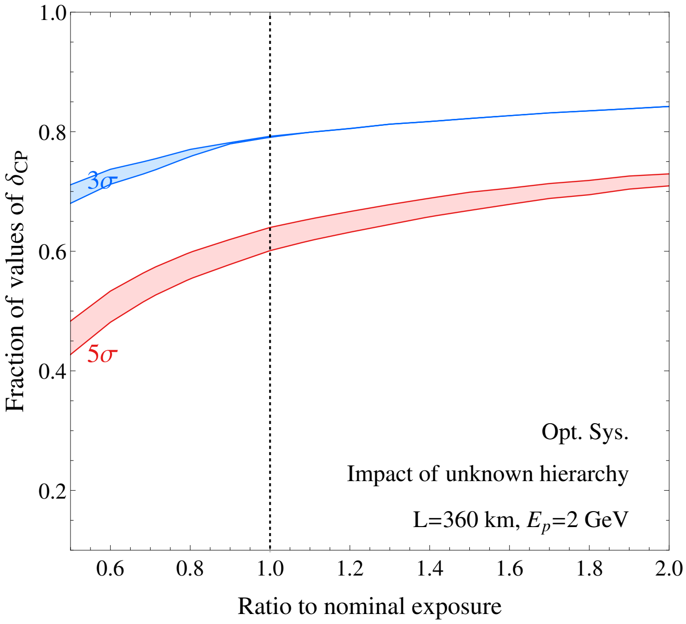

Figure 7: The fraction of the full δ_{CP} range as function of the exposure (10 years correspond to 1) for an unknown mass hierarchy. The lower (upper) curve is for CP violation discovery at 5 σ (3 σ) significance.

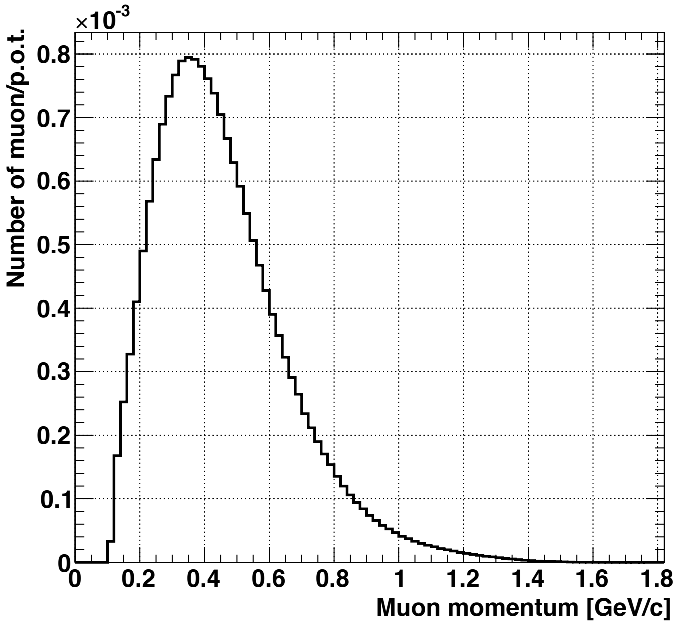

Figure 8: Muon energy distribution per proton on the target at the level of the neutrino facility beam dump.

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