Report from the LPNHE-neutrino group to the LPNHE Scientific Council (May 2018)

1 Executive Summary

The LPNHE neutrino group joined the T2K collaboration in 2006. Originally, the main goal of T2K was the measurement of the θ_{13} *mixing angle. If this turned out to be non-zero, it would open a way to explore* CP *violation in the lepton sector.*

After the discovery of oscillations in both solar and atmospheric neutrinos, there remained three missing pieces in the overal oscillation picture: the third mixing angle θ_{13} *, the mass hierarchy i.e. the sign of* Δm^2_{31} *and the CP violating phase* δ_{CP}*. The mixing angle* θ_{13} *is accessible through the observation of* $\nu_\mu \to \nu_e$ *appearance in accelerator long baseline experiments (T2K and NO*ν*A) or in* $\bar{\nu}_e$ *disappearance at nuclear reactors (Daya-Bay, RENO, Double Chooz).*

The T2K experiment took advantage of a few key elements: the new high intensity proton accelerator at J-PARC (Tokai, Japan), the first use of the off-axis beam technique which allows for a very narrow band neutrino energy tuned for maximizing the oscillation probability at the far detector, which is the high-performance Super-Kamiokande water Cherenkov detector. A near detector (ND280) was built inside the former UA1/NOMAD magnet in order to precisely measure the beam composition prior to oscillations and to quantify potential sources of backgound to ν_e *appearance.*

Data taking in T2K started in 2010 and was abruptly interrupted by the terrible Tohoku earthquake of March 2011. Although it represented only 2% of the expected statistics of the experiment, the data taken previously allowed us to publish the "first indication of an electron neutrino appearance from an accelerator-produced off-axis muon neutrino beam" in June 2011 and to demonstrate a non-zero value for θ_{13}*. This was later confirmed by reactor experiments at the* 5σ *level. The large value found for* θ_{13} $(\sin^2 2\theta_{13} \approx 0.1)$ *opened the possibility to study CP violations in the lepton sector already with currently running experiments such as T2K and NO*ν*A.*

The T2K analysis strategy to extract oscillations parameters relies on a comparison of the predicted (ν_μ *and* ν_e*) spectra at Super-Kamiokande, assuming no oscillations, with the actually observed spectra. Predictions are based on a modelling of the beam line and the neutrino parent hadron production by 30 GeV protons on a carbon target, constrained by the near detector measured spectra and by the NA61/SHINE hadroproduction measurements. At the ∼600 MeV peak energy, approximately 1% of the neutrino flux is due to the intrinsic* ν_e *component of the beam. The overall flux uncertainty estimated through beam simulation is* $\approx 10\%$*. Further improvement down to* $\approx 5\%$ *is to be expected soon, as the new NA61/SHINE measurements with the T2K replica target are added to the flux model.*

Following the first hints of ν_e *appearance published in 2011 and the huge work necessary to restart the experiment after the earthquake, T2K has successfully pursued the study of* $\nu_\mu \to \nu_e$ *appearance and was the first experiment to establish neutrino oscillations in the appearance mode with more than* 7σ *in 2013.*

In parallel with this important study of $\nu_\mu \to \nu_e$*, the collaboration has also invested a lot of efforts in producing a solid* ν_μ *disappearance analysis, resulting in a set of gradually improving results and publications. Since 2014, T2K has been providing the world best measurement of* $\sin^2\theta_{23}$*.*

In 2015, the first combined analysis of $\nu_\mu \to \nu_e$ *and* ν_μ *disappearance was performed and published. The large appearance signal observed by T2K together with the precise measurement of* θ_{13} *by reactor experiments allowed to put first constraints on the CP-violation phase* δ_{CP}*,* *favouring values close to* $-\pi/2$ *which is the value that maximizes the* ν_e *appearance probability.*

In addition to those oscillation analyses, the good knowledge of neutrino fluxes in T2K was used to perform a set of dedicated neutrino cross-section measurements with the near detector complex. In particular, the first ν_e *charged current (CC) differential cross-section measurement at energies of the order of 1 GeV was published, as well as several double differential* ν_μ *CC cross-sections with or without reconstructed protons or pions in the final state.*

In order to improve the sensitivity of the experiment to δ_{CP}*, T2K started anti-neutrino mode data taking in 2014 so as to compare the* ν_e *and* $\bar{\nu}_e$ *appearance probabilities. The effect of* δ_{CP} *is opposite for neutrinos and anti-neutrinos, so that a value of* $\delta_{CP} = -\pi/2$ *would minimize the* $\bar{\nu}_e$ *appearance probability.*

A combined analysis of ν_e *and* $\bar{\nu}_e$ *data has been recently performed by the collaboration. The first direct indication of CP violation in the lepton sector has been obtained with CP-conserving values of* $\delta_{CP} = 0$ or π *excluded at more than* 2σ *when T2K data are combined with reactor constraints.*

These results which were obtained with $\approx 30\%$ *of T2K approved statistics strengthen the case for a continuation of data taking (T2K-II project) aiming at* 20×10^{21} *POT in order to establish CP violation at better than* 3σ *if the currently favoured value is the true one.*

An upgrade of the T2K off-axis near detector ND280 is being prepared and the LPNHE neutrino group is involved in this activity. This is particularily important in view of the third generation long baseline neutrino oscillation experiment T2HK (with the huge water Cherenkov Hyper-Kamiokande as far detector) presently under preparation in Japan.

The main contributions of the LPNHE neutrino group to the above-described results are:

- *participation in construction and operation of the ND280;*
- *crucial contributions to the ND280 data analysis;*
- *important input to the oscillation analysis via the fit of ND280 data;*
- *dedicated involvement in the NA61/SHINE data-taking and analysis for T2K with both thin and replica targets; usage of these data for improved predictions of neutrino and anti-neutrino fluxes in T2K;*
- *coordination of working groups within T2K and NA61/SHINE;*
- *preparation of scientific publications on behalf of T2K and NA61/SHINE collaborations;*
- *participation in the ND280 upgrade: detector optimization and construction of new sub-detectors;*
- *initial work together with physicists from LLR and CEA to define a common french hardware contribution to the Hyper-Kamiokande project.*

1.1 Group members and responsibilities

Physicists

Bernard Andrieu	*CNRS-Chargé de Recherche*
Jacques Dumarchez	*CNRS-Directeur de Recherche* *Group leader; Magnet and TPC expert;* *member of the publication board*
Claudio Giganti	*CNRS-Chargé de Recherche* *TPC expert; Run coordinator;* *Convenor of the T2K oscillation analysis group*
Luca Scotto Lavina	*CNRS-Chargé de Recherche*
Jean-Michel Levy	*CNRS-Chargé de Recherche (benevole)*
Boris Popov	*CNRS-Directeur de Recherche* *Magnet and TPC expert; convenor of the T2K-NA61 group;* *co-convenor the T2K-beam group (till Feb,2018)*; *convenor of the NA61 software and analysis groups*
???	*SU-Assistant Professor, starting from September,2018*
Laura Zambelli	*PhD student till October,2013*
Pierre Bartet-Friburg	*PhD student till October,2016*
Matej Pavin	*PhD student till October,2017*
Simon Bienstock	*PhD student till October,2018*

Engineers

Jean-Marc Parraud	*CNRS-assistant d'ingénieur; design of the FEC board*
Francois Toussenel	*CNRS-ingénieur de recherche; design of the FEC board*
William Ceria	*CNRS-assistant d'ingénieur; mechanics for the new TPCs*
Yann Orain	*CNRS-assistant d'ingénieur; mechanics and cooling for the new FEC boards*
Diego Terront	*CNRS-ingénieur d'études; data acquisition for the TPCs*

1.2 Funding status

Our budget (in k€) over the last six years is summarized in the following table (in parentheses our request for the budget).

year	**T2K+NA61 miss+equip**	**T2K-CF**	**NA61-CF**	**WA105 miss+equip**
2013	33 (60+20)	25	8 (8)	-
2014	35 (50+10)	22	8 (11)	0+18 (10+35)
2015	30 (45+10)	11	10 (10)	5+0 (9+92)
2016	36 (50+10)	14	10 (10)	6+15 (8+16)
2017	40 (45+10)	17	10 (10)	0
2018	47 (62+5)	?	10 (10)	-

2 Activities during the last 5 years

2.1 T2K long-baseline neutrino oscillation experiment

At the beginning of the 21^{st} century, with the neutrino oscillation phenomenon definitely established, the next important question in neutrino physics was the determination of the last unknown parameter of the Pontecorvo-Maki-Nakagawa-Sakata mixing matrix U_{PMNS} – the third mixing angle θ_{13}, for which only upper limits existed. The two preferred experimental ways of measuring θ_{13} are long baseline experiments looking for appearance of ν_e in a ν_μ accelerator beam, or disappearance of $\bar{\nu}_e$ from a nuclear reactor.

Since 2006 the LPNHE group has chosen to participate in the next generation accelerator neutrino experiment - the **T2K project** in Japan (current spokesperson Prof. Tsuyoshi Nakaya, Kyoto University; previous spokesperson Takashi Kobayashi, KEK). This choice not only relates to our better knowledge of accelerator neutrino experiments, but mainly to the fact that such an experiment can provide rich results in the field of neutrino physics, even beyond the oscillation question, as e.g. the NOMAD experiment at CERN [NOMAD-1] has amply demonstrated.

The long baseline T2K neutrino experiment is studying oscillations of an off-axis muon neutrino beam between the Japan Proton Accelerator Research Complex (J-PARC) and the Super-Kamiokande (SK) detector, 295 km away, with special emphasis on measuring the mixing angle θ_{13} by observing the sub-dominant $\nu_\mu \to \nu_e$ oscillation. At the same time the T2K experiment can perform high precision measurements of the ν_μ disappearance and hence of the Δm^2_{32} and θ_{23} parameters.

We were first involved in the construction and operation of the near detector, ND280, a magnetized off-axis tracking detector located at a distance of 280 m from the target, housed inside the magnet reused from the UA1/NOMAD experiments. The main part of ND280 is a tracker, composed by two Fine Grained Dectectors (FGD) interleaved with three Time Projection Chambers (TPC). The goals of the near detector are to measure the neutrino energy spectrum, flavor content, interaction rates of the unoscillated neutrino and anti-neutrino beams, and to predict the unoscillated (anti-)neutrino spectrum at Super-Kamiokande.

Over the last five years, the LPNHE group members had the following important responsibilities within the T2K collaboration:

- **members of the Analysis Steering Group**
- **member of the Speakers Board**
- **member of the Publication Board**
- **co-convenor of the neutrino oscillation group** (from 2016)
- **co-convenor of the Near Detector ν_e group** (from 2012 to 2015)
- **co-convenor of the Near Detector exotics group** (from 2015 to 2016)
- **co-convenor of the beam group** (from 2011 till February,2018)
- **convenor of the T2K-NA61 group**
- **responsibles of 4 paper committees (2 for T2K and 2 for NA61/SHINE), members of 14 paper committees (7 for T2K and 7 for NA61/SHINE)**.

In addition, during the T2K data-taking periods (from Run 1 till Run 9) LPNHE group members were acting as **on-call experts for the UA1/NOMAD magnet** and as **responsible for the**

TPC operation. During one data-taking period the **run coordinator** responsibility has also been taken care of by the LPNHE-neutrino group.

The analysis activities of the LPNHE group have been initially focused on the analyses of the Near Detector data. We have been responsible for the analyses of the Near Detector ν_e and exotics group that lead to four publications.

One of the PhD students of the group, Pierre Bartet, has developed an analysis to select ν_μ interactions with outgoing muon at large angle and backward with respect to the neutrino direction. This selection clearly showed the strengths and the weaknesses of the actual ND280 configuration and was the basis for the design of the ND280 upgrade that will be discussed in following sections of this document. This selection was then used for a cross-section analysis that has been recently published [T2K-31].

Since 2016 the main interest of the group shifted towards the T2K oscillation analysis. Another PhD student from our group, Simon Bienstock, has been responsible for the calculation and implementation of the ND280 constraints to the T2K oscillation analysis presented in Summer 2017 and he is currently working on the oscillation analysis that will be presented at the Neutrino'2018 conference. We are also heavily involved in the sensitivity studies that are being used for the design of the upgraded near detector.

In T2K the muon neutrino beam is produced as the decay products of pions and kaons generated by the interaction of the 30 GeV proton beam from J-PARC with a 90 cm-long graphite target. Dedicated hadron production measurements performed in the framework of the NA61/SHINE experiment at CERN are being used for precise predictions of neutrino and anti-neutrino fluxes in T2K [T2K-8]. Our PhD students - Laura Zambelli and Matej Pavin - have made crucial contributions to the analysis of NA61/SHINE data collected with a thin carbon target and a T2K replica target, see below.

The T2K experiment employs the off-axis method to generate a narrow-band neutrino beam and this is the first time this technique has been used in a study of neutrino oscillations. The method utilizes the fact that the energy of a neutrino emitted in the two-body pion (kaon) decay, the dominant mode for the neutrino production, at an angle relative to the parent meson direction is essentially determined by transverse momentum conservation between the decaying particle frame and the lab frame. By positioning a detector at an angle relative to the target (off-axis angle), one will therefore see neutrinos with a narrow spread in energy. The peak energy of the neutrino beam can be varied by changing the off-axis angle. In the case of T2K, the off-axis angle is set at 2.5° so that the neutrino beam at SK has a peak energy at about 0.6 GeV, near the expected first oscillation maximum. This maximizes the effect of the neutrino oscillations at 295 km as well as reduces the contamination from background events.

The secondary charged pions and kaons generated in the target are focused by magnetic horns. The magnetic horns were originally set to focus positively charged particles, thus producing a beam of neutrinos towards the T2K detectors (ν–mode). By inverting the direction of the horn current one can focus negatively charged particles, and, as a consequence, produce a beam of anti-neutrinos ($\overline{\nu}$–mode). The T2K experiment is taking data also in this configuration since 2014.

2.1.1 Summary of the T2K oscillation results (up to May,2018)

T2K started data taking in ν–mode in 2010 and publishes roughly 6 papers per year on different topics, from oscillation analyses to measurements of neutrino cross-sections. For the oscillation results, we will give here a brief summary of previous results and discuss in some more details the last T2K analysis presented in Summer 2017. This analysis showed first hints of CP violation in the lepton sector, by excluding CP conserving values ($\delta_{\rm CP}$ =0 or π) at more than 2σ. A paper describing these results is currently under preparation.

With its first data, corresponding to 1.43×10^{20} protons on target (POT), T2K **observed indications of $\nu_\mu \rightarrow \nu_e$ appearance** [T2K-1]. Six candidate ν_e events passed all selection criteria at the far detector. In a three-flavor neutrino oscillation scenario with $\sin^2 2\theta_{13} = 0$, the expected number of such events is 1.5±0.3(syst.). Under this hypothesis, the probability to observe six or more candidate events is 7×10^{-3}, equivalent to a 2.5σ significance. The publication quickly became famous and by now has more than 1300 citations in the INSPIRE database. In 2012 this T2K article was awarded the prize of the french science magazine "La Recherche": the LPNHE group members received the prize in the name of the T2K Collaboration. It is important to stress that in 2016 the T2K collaboration got a Breakthrough Prize in fundamental physics.

Later, with data corresponding to 3.01×10^{20} POT the T2K collaboration reported **evidence for electron neutrino appearance** [T2K-4]. 11 electron neutrino candidate events at the SK detector were observed, for an expected background of 3.3 ± 0.4(syst.) events. The background-only hypothesis is rejected with a p-value of 0.0009 (3.1σ),

Then, in April 2014 with more data accumulated (6.57×10^{20} POT) and with reduced systematic uncertainties, it became possible **to firmly establish the observation of $\nu_\mu \rightarrow \nu_e$ appearance** and more generally **the existence of neutrino oscillations in the appearance mode** [T2K-2]. A total of 28 electron neutrino events were detected with an energy distribution consistent with an appearance signal, corresponding to a significance of 7.3σ when compared to 4.92 ± 0.55 expected background events. When combining this result with the current best knowledge of oscillation parameters including the world average value of θ_{13} from reactor experiments, some values of the CP-violation phase $\delta_{\rm CP}$ are disfavored at the 90% C.L.

In parallel with $\nu_\mu \rightarrow \nu_e$ appearance analysis, we have also reported the first measurements of ν_μ disappearance in the T2K experiment [T2K-7]. During the last years these results have been updated several times, with increasing levels of precision and with more and more careful studies of the systematic effects on neutrino cross-sections that are mostly affecting ν_μ disappearance given the larger statistics with respect to ν_e appearance. In publications up to 2014, T2K fitted the energy-dependent ν_μ oscillation probability to determine oscillation parameters θ_{23} and Δm^2_{32}. In all the analyses T2K has always preferred a value of θ_{23} compatible with the one leading to maximum mixing (θ_{23} =45°).

An important milestone for T2K has been the **first analysis that combine measurements of muon neutrino disappearance and electron neutrino appearance** to estimate four oscillation parameters – $|\Delta m^2_{32}|$, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ_{CP} – and the mass hierarchy [T2K-3]. Frequentist and Bayesian intervals are presented for combinations of these parameters, with and without including recent reactor measurements. At 90% confidence level and including reactor measurements, we exclude the region $\delta_{\rm CP}$=[0.15,0.83]π for normal hierarchy and $\delta_{\rm CP}$=[-0.08,1.09]π for inverted hierarchy. The analysis framework developed to perform this analysis has then been extended to take into account also samples selected in $\overline{\nu}$–mode.

As already mentioned previously, T2K is taking data in $\overline{\nu}$–mode since 2014. The first analysis of the collected anti-neutrino data, corresponding to 4.011×10^{20} POT, was presented in 2015.

In particular, T2K reported its first measurements of the parameters governing the disappearance of $\bar{\nu}_\mu$ in an off-axis beam due to flavor change induced by neutrino oscillations [T2K-32], [T2K-24]. The θ_{23} and Δm^2_{32} parameters measured from $\overline{\nu}_\mu$ disappearance can be compared with the same parameters obtained from ν_μ disappearance. Under CPT invariance no differences are expected between the two sets of parameters. In its most recent search, based on 7.482×10^{20} POT in neutrino running mode and 7.471×10^{20} POT in anti-neutrino mode, T2K obtained, $\sin^2\theta_{23} = 0.51^{+0.08}_{-0.07}$ and $\Delta m^2_{32} = 2.53^{+0.15}_{-0.13} \times 10^{-3}$ eV$^2/c^4$ for neutrinos, and $\sin^2\bar{\theta}_{23} = 0.42^{+0.25}_{-0.07}$ and $\Delta\bar{m}^2_{32} = 2.55^{+0.33}_{-0.27} \times 10^{-3}$ eV$^2/c^4$ for anti-neutrinos (assuming normal mass ordering). No significant differences between the values of the parameters describing the disappearance of muon neutrinos and anti-neutrinos were observed and in both cases θ_{23} is compatible with maximal mixing.

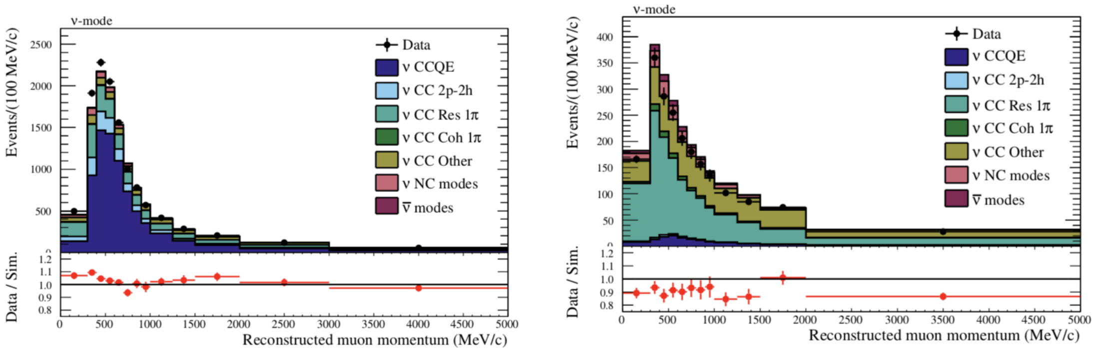


Figure 1: Momentum distribution of outgoing muons for ν_μ CC-0π^+ (left) and CC-1π^+ (right) samples at ND280: measurements are compared with MC predictions.

At the beginning of 2017 **T2K reported its first results in the search for CP violation in neutrino oscillations** using appearance and disappearance channels for neutrino- and anti-neutrino-mode beam [T2K-26] that has been later updated with the inclusion of an additional sample of electron neutrino candidates at Super-Kamiokande in which a pion decay has been tagged [T2K-21]. These results showed that **the hypothesis of CP conservation (δ_{CP}=0 or π) is excluded at 90% confidence level**

This analysis has been updated during the summer of 2017, when T2K presented the first hints at the 2σ level of CP violation in the lepton sector. These results are based on the analysis of 14.7×10^{20} POT in neutrino mode and 7.6×10^{20} POT in anti-neutrino mode, corresponding to $\sim$ 30% of the total expected T2K statistics.

For the oscillation analyses, the expected event rates and spectra at SK are predicted based on a model of the neutrino flux and of neutrino cross-sections. The first is based on the NA61/SHINE hadroproduction measurements, that allow to reduce the flux errors below 10%. The latter is based on models that are tuned using measurements from different neutrino experiments (mostly MiniBooNE and Minerva). Uncertainties on event rates and spectra of the order of 15% would be expected if only those data were available.

Crucial inputs to the T2K oscillation analyses are then the measurements at the Near Detector. In the ND280 tracker, a total of 14 samples of ν_μ and $\overline{\nu}_\mu$ charged current interactions are selected in the FGD1 and in the FGD2 with muons precisely measured in the TPCs. The samples are separated according to the number of pions observed in the final state (0, 1, more than 1). Examples of the distributions of outgoing muon momentum are shown in Fig. 1.

The 14 event samples are binned in p_μ and $\cos\theta_\mu$. The likelihood assumes that the observed number of events in each bin follows a Poisson distribution, with an expectation calculated according to the flux, cross-section and detector systematic parameters. A multivariate Gaussian likelihood function is used to constrain these parameters in the fit. The fitted neutrino cross-section and unoscillated SK flux parameters are passed to the oscillation analysis, using a covariance matrix to describe their uncertainties. The fit results for these parameters are shown in Fig. 2: it is clear that the uncertainties are reduced. A systematic uncertainty in the range of $\sim$4–7% is obtained.

The event numbers selected at SK in 5 samples defined in the legends of the Fig. 3 are presented in Tab. 1 and compared with the expected numbers of events for different values of $\delta_{\rm CP}$. The spectra are shown in Fig. 3. As it is clear from Tab. 1, $\delta_{\rm CP}$ only affects the e-like samples and values of $\delta_{\rm CP}$ close to -$\pi/2$ tend to increase the ν_e appearance probability, while decreasing the $\overline{\nu}_e$ probability. This is exactly what is observed in the ν-mode ($\overline{\nu}$-mode), where 74 (7) single-ring e-like events are observed while 62 (9) are expected if $\delta_{\rm CP} = 0$ or π.

The five samples presented in Table 1 are then fitted together in order to extract the oscillation

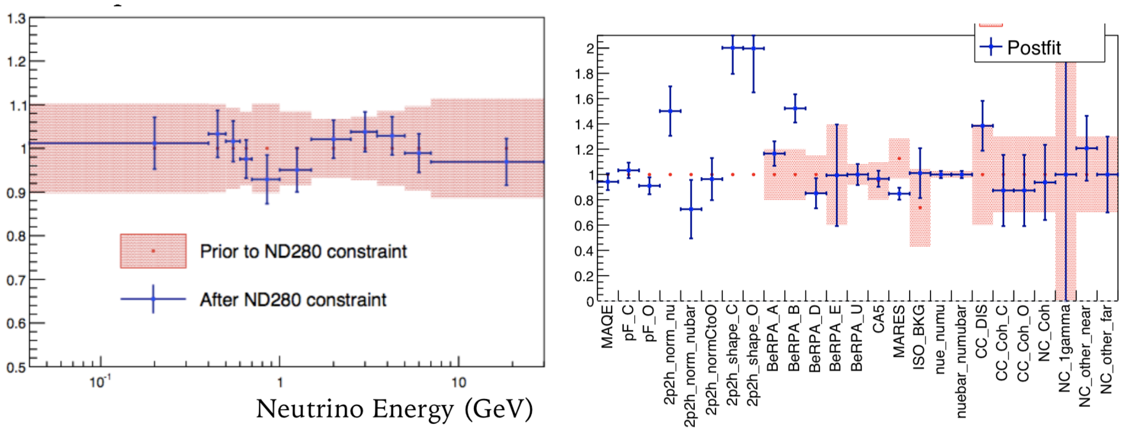


Figure 2: Flux (left) and cross-section (right) parameters before (red) and after (blue) the Near Detector fit.

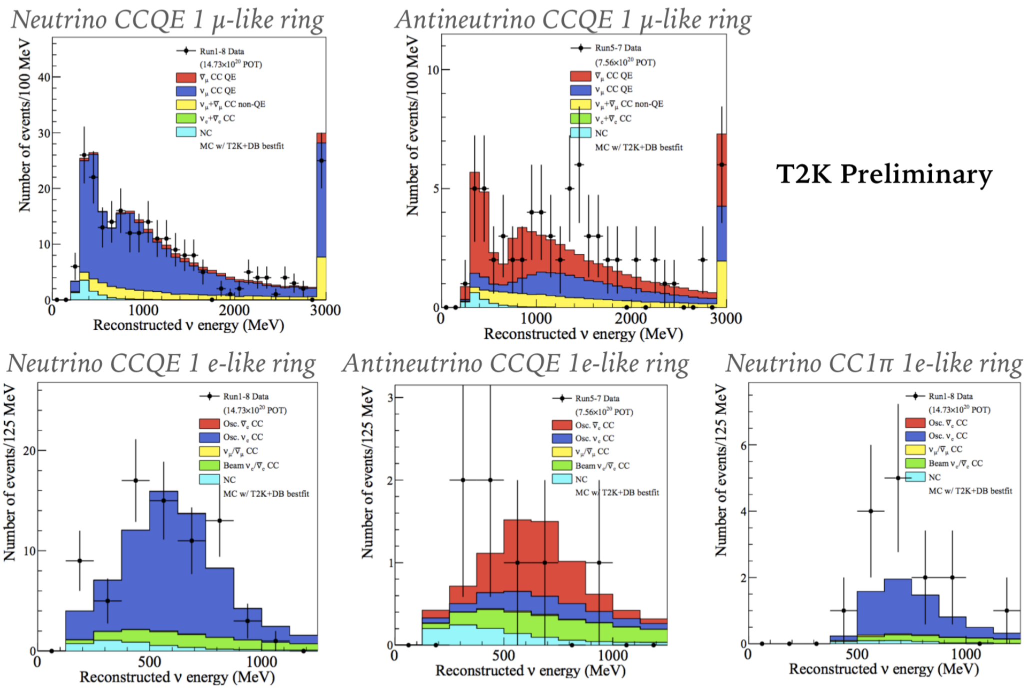
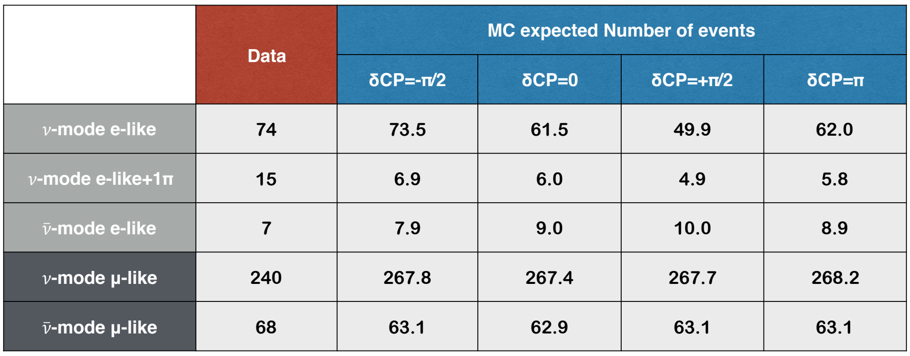


Figure 3: Observed spectra at SK in the five samples used for the oscillation analyses



	Data	MC expected Number of events			
		δCP=-π/2	δCP=0	δCP=+π/2	δCP=π
ν-mode e-like	74	73.5	61.5	49.9	62.0
ν-mode e-like+1π	15	6.9	6.0	4.9	5.8
$\bar{\nu}$-mode e-like	7	7.9	9.0	10.0	8.9
ν-mode μ-like	240	267.8	267.4	267.7	268.2
$\bar{\nu}$-mode μ-like	68	63.1	62.9	63.1	63.1

Table 1: Observed and expected numbers of events at SK for different values of δ_{CP}.

parameters θ_{23}, Δm^2_{32}, θ_{13}, and δ_{CP}. The value of θ_{13} can either be a free parameter in the fit or it can be constrained to the precise measurement of the reactor experiments. The two cases are shown in Fig. 4: both fits prefer values of δ_{CP} close to $-\pi/2$ and, when the reactor constraint is included, the CP conserving values 0 and π are excluded at more than two sigma. θ_{23} and Δm^2_{32} are also precisely determined by T2K: in particular the value of θ_{23} is still compatible with maximal mixing as shown in Fig. 5. It should be noted that in Fig. 5 some tensions are observed between T2K and the first published NOνA results for θ_{23} [15]. In a recent update of the oscillation analysis of NOνA, θ_{23} is found to be compatible with maximal mixing also in their analysis, and currently there is no tension between T2K and NOνA results.

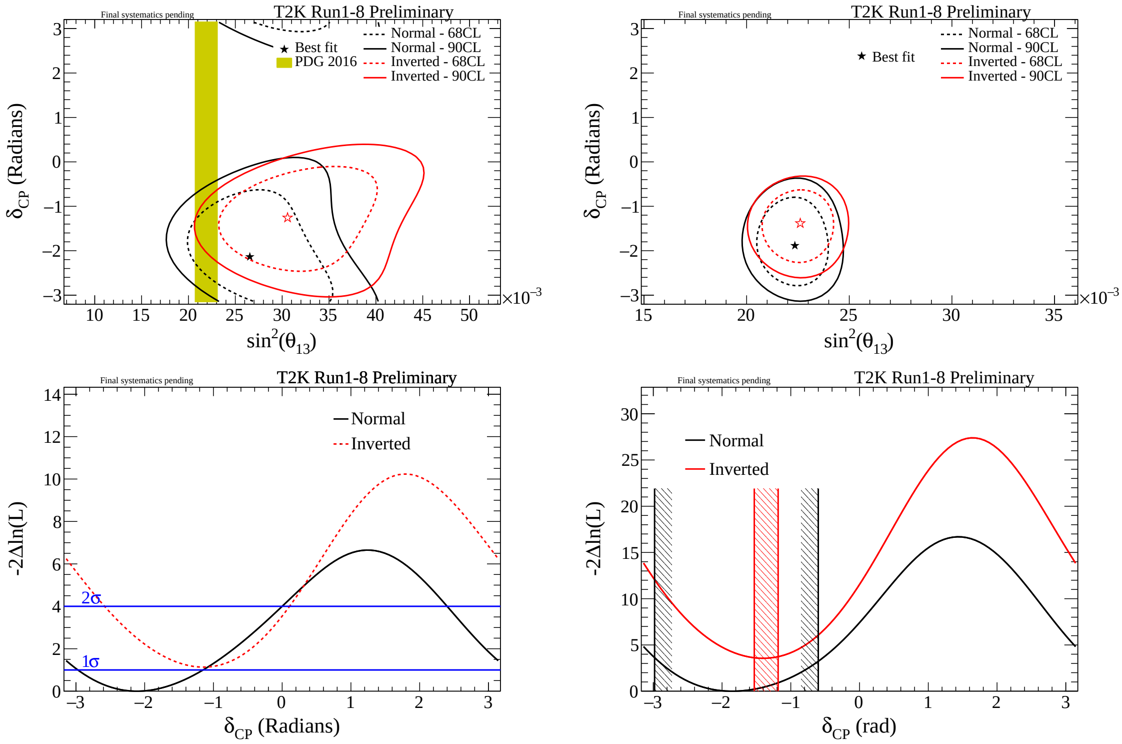


Figure 4: Measurements of the oscillation parameters θ_{13} and δ_{CP} without (left) and with (right) the reactor constraint. Note the different horizontal scale for the top-right plot.

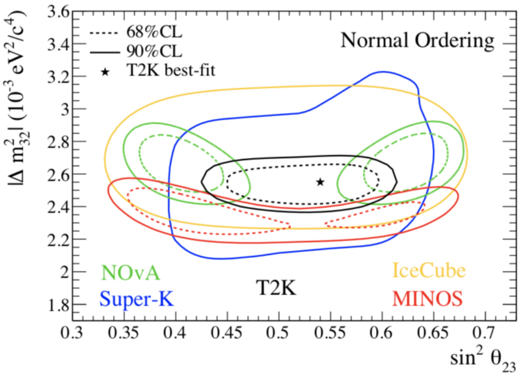


Figure 5: Measurements of the oscillation parameters θ_{23} and Δm^2_{32} from T2K, compared to other experiments.

In October 2017, T2K has restarted data taking in $\overline{\nu}$–mode. The accelerator can stably run at 475 kW and this will hopefully allow to double the $\overline{\nu}$–mode statistics with data taken until May 2018. Updated oscillation results with this additional statistics will be released during Summer 2018.

2.1.2 Near Detector analyses

Beyond the oscillation analysis, various cross section measurements have already been performed [T2K-10–18,20,22,23,29-31,33] and are being conducted at the near detector taking advantage of the high statistics and of the good quality of reconstructed events.

The LPNHE group was initially involved in the activities of the ND280 ν_e and exotics groups. The goal of the ND280 ν_e group is the measurement of the intrinsic ν_e component in the T2K beam. This component is the main background to the ν_e appearance signal at SK and it arises from the decay of muons and kaons produced in the beamline. This component is expected to represent about 1.2% of the total neutrino flux in T2K and its selection is difficult due to the large amount of different backgrounds, especially muons produced in ν_μ charged current interactions that are ~ 100 times more frequent than ν_e interactions in ND280.

The combination of the particle identification (PID) capabilities of three time projection chambers (TPC) and a set of electromagnetic calorimeters (ECals) is used to distinguish electrons from muons, allowing the selection of a clean sample of ν_e charged current (CC) interactions, with the main background composed by γ conversions in the FGD producing an e^+e^- pair in which only the electron is reconstructed in the TPC. This background is directly measured through a control sample of γ conversions in which both, the e^+ and the e^-, are reconstructed in the TPC.

The main results of the ND280 ν_e (and exotics) groups have been published in the following three papers:

- In [T2K-11] the goal was to measure the beam ν_e component and compare it with the expected number of ν_e interactions predicted by using exactly the same model as the one used for the T2K oscillation analyses. This was done in order to confirm the validity of the method chosen by T2K of using the Near Detector to constrain the flux and cross-section uncertainties. To extract the beam ν_e contamination we performed a likelihood fit and found that the observed number of events is in good agreement with the prediction (data/MC $= 1.01 \pm 0.10$), providing a direct validation of the method used in all T2K oscillation analyses. This measurement is particularly important because the intrinsic ν_e component is the main background for all proposed long-baseline neutrino oscillation experiments aiming to measure CP violation in the lepton sector via observation of the different oscillation appearance probabilities between ν_e and $\overline{\nu}_e$, and we proved that this component can be measured with a properly designed Near Detector.

- In [T2K-14] we used the ν_e selection in FGD1 to measure the ν_e cross section on carbon (the FGD2 has layers of water interleaved with plastic scintillators so it is not used in the cross-section measurement). This was the first measurement of a ν_e cross section since the Gargamelle bubble chamber ν_e CC inclusive cross-section results published in 1978. The total flux-averaged ν_e charged current cross section on carbon is measured to be $(1.11 \pm 0.09(\mathrm{stat}) \pm 0.18(\mathrm{syst})) \times 10^{-38}$ cm^2/nucleon. The differential and total cross section measurements agree with the predictions of two leading neutrino interaction generators, NEUT [11, 12] and GENIE [13]. ν_e cross sections are very important in the searches for CP violation in the lepton sector since near detectors constrain flux and cross-section systematic uncertainties by using only ν_μ interactions. Theoretical differences are expected between ν_e and ν_μ cross sections, and measuring those with data is critical to understand the systematics in the CP violation search.

- In [T2K-15] we used the ν_e selection to perform a first search for sterile neutrinos at ND280 in the ν_e disappearance channel. Sterile neutrinos are often invoked to explain a few experimental results that do not fit in the standard PMNS framework. In particular LSND and MiniBooNE have observed an excess of ν_e for neutrinos with an L/E ratio similar to the one of ND280. Another anomaly is the deficit of ν_e originating from intense radioactive sources in the calibration of the solar neutrino gallium detectors SAGE and GALLEX and $\overline{\nu}_e$ rates near nuclear reactors. The T2K result excludes part of the gallium anomaly and a small part of the reactor anomaly allowed regions. The current T2K limit at 95% C.L. is contained within the region excluded by the combined fit of the solar and KamLAND data. The present results are limited by the small statistics but additional data will allow to put better limits on this channel.

The LPNHE group also participated in the developments of new ν_μ selections at ND280 and in the ν_μ cross-section analyses. One of the most important cross-section analyses performed up to now at ND280 is the measurement of muon neutrino charged-current interactions on carbon without pions in the final state [T2K-31]. For the first time the measurement is reported as a flux-integrated, double-differential cross-section in muon kinematic variables ($\cos\theta_\mu$, p_μ), without correcting for events where a pion is produced and then absorbed by final state interactions. The measurements compare favorably with recent models which include nucleon-nucleon correlations but, given the present precision, these measurements do not solve the degeneracy between different models. The data also agree with Monte Carlo simulations which use effective parameters that are tuned to external data to describe the nuclear effects. The total cross-section in the full phase space is $\sigma = (0.417 \pm 0.047(syst) \pm 0.005(stat)) \times 10^{-38}$ cm^2 nucleon^{-1} and the cross-section integrated in the region of phase space with largest efficiency and best signal-over-background ratio ($\cos\theta_\mu$ >0.6 and p_μ >200 MeV) is $\sigma = (0.202 \pm 0.0359(syst) \pm 0.0026(stat)) \times 10^{-38}$ cm^2 nucleon^{-1}.

Thanks to the work of one of our PhD students, Pierre Bartet, the group was also at the core of a selection done to improve the angular acceptance of the Near Detector and to perform a measurement of charged current muon neutrino cross sections with 0, 1, or 2 protons in the final state. The selection we developed allowed to increase the angular acceptance of ND280 also for tracks going at large angles and backward with respect to the neutrino direction, mainly by using the time-of-flight information. The efficiency as a function of the angle with respect to the beam is shown in Fig. 6. The importance of this work is attested by the on-going ND280 upgrade project that will be discussed later and that is mainly motivated by the improvement of the angular acceptance of ND280.

These selections, combined with the standard forward selection of ND280, were used to perform a four-differential cross-section measurements in which, for the first time, momentum and angle of the muons were combined with the momentum and angle of reconstructed protons. This is important because the number and the properties of the protons emitted in neutrino interactions are affected by nuclear effects that also affect the estimation of the neutrino energy in oscillation analyses. The T2K Near Detector, thanks to its granularity and the presence of a magnetic field, allows for a detailed measurement of the protons emitted in neutrino interactions. This analysis has been recently submitted for publication [16].

2.2 NA61/SHINE hadron production experiment

Being a second generation accelerator neutrino experiment, T2K is also a precision experiment: we felt pretty soon that we needed a dedicated hadron production experiment to control the beam systematics to the level required (less than 5%). A small fraction of the T2K collaboration (essentially 1 japanese group - KEK - and 4 european groups, including LPNHE, Paris) has decided in 2006 to measure the production of charged pions and kaons in proton interactions

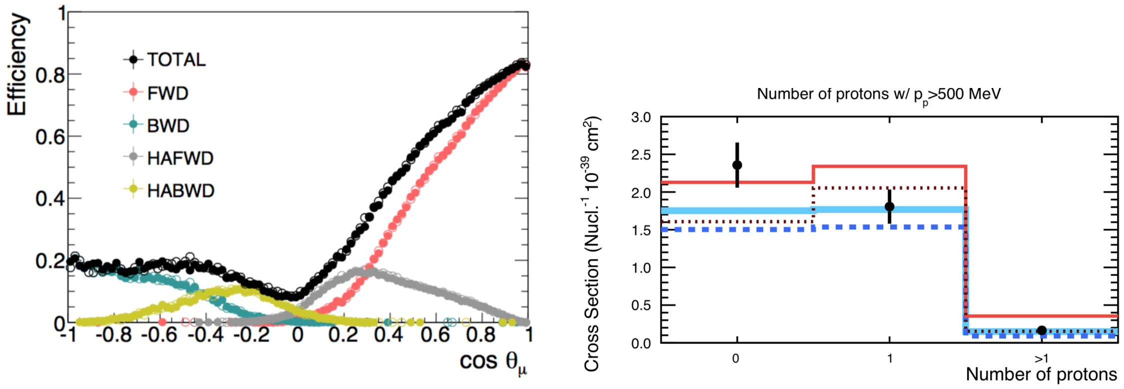


Figure 6: Left: Efficiency of the ND selection as a function of $cos(\theta)$ when the high angle and backward selections are added to the forward selection. Right: cross-section as a function of the number of protons compared to different neutrino generators: NEUT (red), NuWRO [14] without 2p2h (dotted blue), NuWRO SF+2p2h (light blues), NuWRO LFG+2p2h (dotted brown).

at 31 GeV/c with a replica of the T2K Carbon target in the framework of the **NA61/SHINE experiment** at CERN SPS (project leader Prof. Marek Gaździcki, University of Frankfurt). The NA61/SHINE spectrometer [NA61/SHINE-2], also used by an on-going heavy ion experiment, has been refurbished with the help of the T2K groups and data have been taken with a thin (4% λ_{int}) carbon target and with a T2K replica target first in 2007, and then in 2009 and 2010.

In the NA61/SHINE project we have two important responsibilities: **software coordinator** (for the legacy software) and **analysis coordinator for Neutrino (T2K) and Cosmic Ray (CR) experiments**. These activities require organization of regular Vidyo meetings (at least once per two weeks) in order to coordinate the work of about 20 collaborators (involved in the software development and analysis efforts) located in different countries. As a result, we are deeply involved in the NA61/SHINE data calibration and analysis as well as in the coordination of work towards the NA61/SHINE hadron production measurements for T2K with active participation of physicists from Swiss groups, in particular, from the University of Geneva (group leader Prof. Alain Blondel). We also contribute to the activities of the Talk Board and of the Editorial Committee.

The group members were responsible within the collaboration for the preparation of several status reports as well as of the first NA61/SHINE physics papers devoted to the interaction cross sections and charged pion spectra measurements in p+C interactions at 31 GeV/c (analysis of 2007 and 2009 data taken with the thin carbon target). These data together with a more recent publication on the measurement of the production properties of positively charged kaons have been **used in the first T2K oscillation results to improve predictions of the initial neutrino fluxes in the experiment**.

Later, the NA61/SHINE thin-target hadroproduction results have been complemented with measurements of neutral strange particle (K^0_S and Λ) yields [NA61/SHINE-3].

A combined paper on the new better-precision measurements of $\pi^{\pm}$, $K^{\pm}$, K^0_S, Λ and proton production in proton–carbon interactions at 31 GeV/c using a graphite target with a thickness of 4% of a nuclear interaction length has been finalized and published under the supervision of the LPNHE group [NA61/SHINE-10].

Predicting the neutrino flux and energy spectrum is an important component of analyses in accelerator neutrino experiments. In 2013 a detailed paper on the T2K neutrino flux prediction, including the NA61/SHINE input, has been prepared with our active participation [T2K-8]. The results of hadronic interactions modeling is re-weighted using thin-target hadron production data from NA61/SHINE. For the first T2K analyses the uncertainties on the flux prediction were evaluated to be below 15% near the flux peak. They are now reduced down to ∼ 10% thanks to the new NA61/SHINE thin-target measurements. The uncertainty on the ratio of the flux predictions at the far and near detectors is less than 2% near the flux peak.

Special efforts have also been invested into the **first full-scale analysis of the long – T2K replica – target data** collected by NA61/SHINE (Ph.D. thesis by Nicolas Abgrall from the University of Geneva, September 2011). Long-target data are more difficult to reconstruct and analyse but they provide much more directly the information needed for predicting the neutrino flux. As a result of this important activity, in close cooperation with the T2K beam group, we prepared an article which presents details of the experiment, data taking, data analysis method and results from the 2007 pilot run [NA61/SHINE-1]. It is important to stress that the first application of the NA61/SHINE replica-target measurements to the predictions of the T2K initial neutrino flux is described and discussed there.

A detailed analysis of a larger sample of 2009 replica-target data, providing fully-corrected charged pion yields from the surface of the T2K replica target, has recently been finalized (Ph.D. thesis by Alexis Hasler, University of Geneva, June 2015) and published [NA61/SHINE-8].

An ultimate analysis of the high-statistics 2010 replica-target data has been performed by Matej Pavin within the LPNHE-neutrino group (Ph.D. thesis defended in September 2017) [5]. Yields of charged kaons and protons have been measured for the first time, while the precision and the phase-space coverage for $\pi^{\pm}$ measurements have been improved.

The analysis was performed by using a joint energy-loss and time-of-flight particle identification procedure as described in the previous publications devoted to replica target measurements [NA61/SHINE-1,8]. In contrast to other NA61/SHINE analyses, replica-target measurements are performed by extrapolating TPC tracks towards the target surface instead of reconstructing the main interaction vertex. This was done because the T2K neutrino flux actually depends on the longitudinal position of emitted hadrons along the target surface. Therefore, the $\pi^{\pm}$, $\mathrm{K}^{\pm}$ and proton results are presented as double differential yields normalized by the total number of incoming beam protons hitting the target, in bins of momentum, polar angle and longitudinal position along the target surface. The target was subdivided into five longitudinal sections 18 cm in size and the downstream target face. Polar angle and momentum binning is defined for each particle species separately since the size of the bins depends on the available statistics. Extracted yields were fully corrected for various inefficiencies by using multiplicative corrections based on the data and simulations.

Detailed comparisons of the $\pi^{\pm}$, $\mathrm{K}^{\pm}$ and proton yields with the FLUKA2011.2c.5 model [1] as well as with the NuBeam and QGSP_BERT physics lists of GEANT4.10 [2, 3, 4] have also been performed. An example can be seen in Fig. 7 which shows hadrons emitted from the second longitudinal target bin in just one selected polar angle interval. Both, the FLUKA2011.2c.5 and NuBeam GEANT4.10 physics lists predict pion yields within ±30%, whereas QGSP_BERT GEANT4.10 shows larger differences. While all selected models provide reasonable predictions for charged kaon yields, they all fail to predict proton yields. The differences can be larger than a factor of two. A full set of comparisons can be found in Ref. [5].

These new results represent a major milestone for the neutrino-related programme of NA61/SHINE. Reduction of systematic uncertainties on the (anti-)neutrino fluxes down to 5% and below is one of the priorities for the on-going and future neutrino experiments. Publication of these results is in preparation.

The next step is to fully include the final NA61/SHINE measurements in the T2K beam simulation to be as less dependant as possible on hadroproduction models. A good validation of the whole process can be done using the generic tool that we are currently developing at LPNHE for neutrino flux predictions in accelerator experiments: it is based on the Virtual Monte-Carlo (VMC) ROOT package and can treat T2K and NA61/SHINE identically, only the geometry being different and separately given to the package. This work was a part of the Ph.D. thesis by

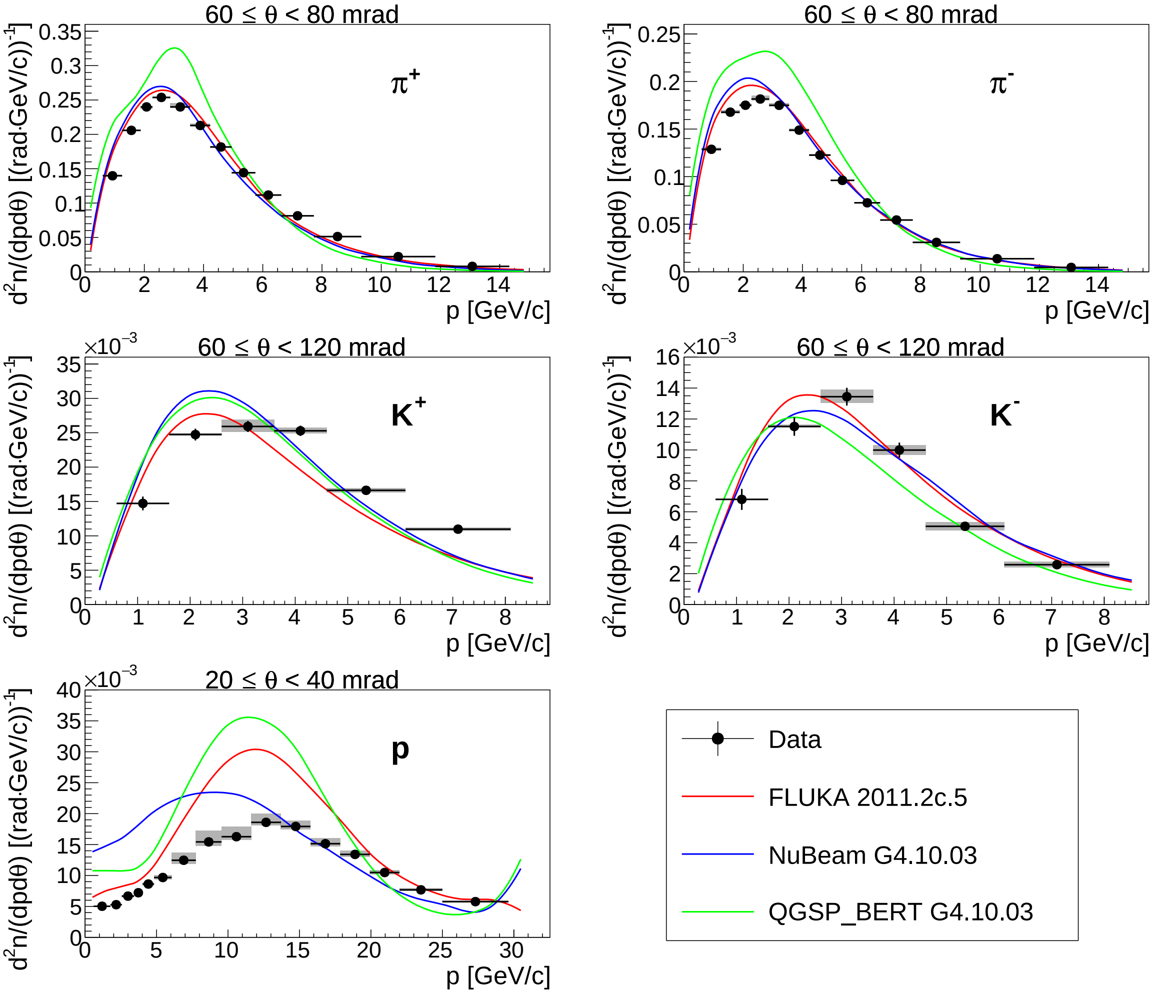


Figure 7: NA61/SHINE measurements of double differential $\pi^{\pm}$, $K^{\pm}$ and proton yields coming from the second longitudinal target bin and one selected polar angle interval. Vertical error bars represent statistical uncertainties, while shaded regions are systematic uncertainties. Lines represent predictions of different MC models: FLUKA2011.2c.5 (red), NuBeam (blue) and QGSP_BERT (green) physics lists of GEANT4.10.

Laura Zambelli (LPNHE) defended in September, 2013 [6].

For validation of available hadronic generators a set of detailed comparisons of hadron production data from the HARP and NA61/SHINE experiments with existing models has been performed. This work has been continued for the physics lists of the GEANT4 simulation toolkit.

The NA61/SHINE Collaboration has also published several important results on hadron production in p+p [NA61/SHINE-4,6,9] and π^-+C [NA61/SHINE-5] interactions.

It is important to stress that we established close contacts with collaborators working on model improvements based on NA61/SHINE data (e.g. Dr. Vladimir Uzhinsky, one of the main developers of the FTF-based physics lists within GEANT4).

To summarize, the HARP and NA61/SHINE hadron production experiments and their relevance for neutrino physics have been consistently recognized and the group members have been invited to discuss them at several international conferences, e.g.

- In May 2012 a contribution “Hadron production measurements with NA61/SHINE” at the Town Meeting “European Strategy for Neutrino Oscillation Physics” held at CERN.
- In June 2012 a review talk on hadron production experiments at the major Neutrino’2012 conference in Kyoto [CONF-1].

- In August 2014 a review talk “Fixed-target hadron production experiments” at the International Symposium on Very High Energy Cosmic Ray Interactions, ISVHECRI 2014, CERN, Geneva [CONF-2].

It is now widely recognized that hadron production experiments have already significantly contributed to recent advances in neutrino physics. An order of magnitude larger event samples for T2K (the 2009 and 2010 NA61/SHINE runs) have been successfully analysed for both thin and T2K replica targets. After full analysis of these data a required precision of 5% on the absolute neutrino fluxes in the T2K near and far detectors could be achieved. An even higher precision will be needed for future accelerator neutrino experiments.

Indeed, future neutrino oscillation experiments at accelerators would require a precision of about 2-3% on the predicted absolute neutrino fluxes. The so-called USNA61 part of the NA61/SHINE scientific programme – an extension of the NA61/SHINE physics program utilizing hadron production measurements for Fermilab neutrino beams [NA61/SHINE-15] – is now officially approved. The physics data-taking period started in October, 2015 and continues till now. Future extension of this program towards T2K-II and T2HK is being prepared.

Moreover, the NA61/SHINE setup is also of interest for the cosmic ray physics community (AUGER and KASKADE experiments as well as experiments studying Galactic cosmic rays interested in antiparticle production, e.g. AMS). We are closely following the related analyses within NA61/SHINE as well as the studies performed for the heavy ion physics community (e.g. precise measurements of hadron production in proton-proton interactions are important as reference data for heavy ion collisions and for tuning of hadron production models).

2.3 The WA105 experiment

During 2014–2017 the LPNHE neutrino group has also been involved in the WA105 experiment at CERN devoted to large-scale neutrino detector demonstrators for phased performance assessment in view of future long-baseline oscillation experiments (originally LBNO in Europe [LAGUNA-LBNO–1-3] and then LBNE/DUNE in the US). The collaboration has defined as priority the construction and operation of a $6 \times 6 \times 6$ m^3 (active volume) double-phase liquid argon (DLAr) demonstrator [WA105–1-3] and a parallel development of the technologies necessary for large magnetized MIND detectors. It is to be constructed and operated in a controlled laboratory and surface environment with test beam access, such as the CERN North Area. Its successful operation and full characterization will be a fundamental milestone, likely opening the path to an underground deployment of larger detectors. The response of the DLAr demonstrator should be measured and understood with an unprecedented precision in a charged particle test beam (0.5-20 GeV/c).

The original plan of the LPNHE group was to develop a hardware contribution to the WA105 experiment around a development of HV feedthroughs. Unfortunately, within WA105 there was not enough desire to share the expertise and, finally, the HV feedthroughs were designed and produced by an Italian company and the LPNHE group only contributed to cover the construction cost.

The LPNHE neutrino group has made contributions to the software development for WA105. In particular, looking for a synergy with on-going LAr activities in the US, we have installed at CERN and at CCIN2P3 (Lyon) the LArSoft framework being developed at Fermilab, see https://cdcvs.fnal.gov/redmine/projects/larsoftsvn/wiki. The LArSoft framework is a collection of many software packages, including neutrino event generator (GENIE), detector description (GEANT4), analysis tools (ROOT), pattern recognition (PANDORA), etc. This framework is now being used by the WA105 collaboration members.

This activity will not be pursued given the choice made by the LPNHE-neutrino group to participate in the Hyper-Kamiokande project.

3 Future activities

3.1 T2K-II and ND280 upgrade

The most recent results of T2K show intriguing hints that CP might be violated in the lepton sector. These results are obtained with statistics of 2.2×10^{21} POT, corresponding to about 30% of the total T2K approved statistics. These results are also supported by the most recent analyses of NOνA and Super-Kamiokande that both prefer large CP violation ($\delta_{\rm CP}$ $\sim$-$\pi/2$) and a normal mass ordering. If true, those are the most favorable values for early discoveries by long-baseline experiments, with the exclusion of CP conserving values and a determination of the mass ordering that is within reach of T2K and NOνA.

These goals can be achieved by T2K and NOνA before the next generation of experiments will be operational if the following conditions are satisfied.

1. more statistics have to be collected by the two experiments;
2. better understanding of flux and cross-sections systematic uncertainties;
3. combination of the T2K and NOνA oscillation analyses.

In order to fulfill condition #1, the T2K collaboration has proposed an extension to the currently approved T2K data-taking program (7.8×10^{21} POT). This will allow to extend the T2K running time until 2026 and to collect a statistics of 20×10^{21} POT, aiming at initial observation of CP violation with 3σ or higher significance for the case of maximum CP violation [T2K-27,28]. This is justified by the fact that the originally approved statistics of 7.8×10^{21} corresponds to the statistics at which systematic uncertainties would have been dominant in case of small θ_{13}. Today we know that θ_{13} is large and an increased statistics would improve the sensitivity of the experiment to measure $\delta_{\rm CP}$, as shown in Fig. 8.

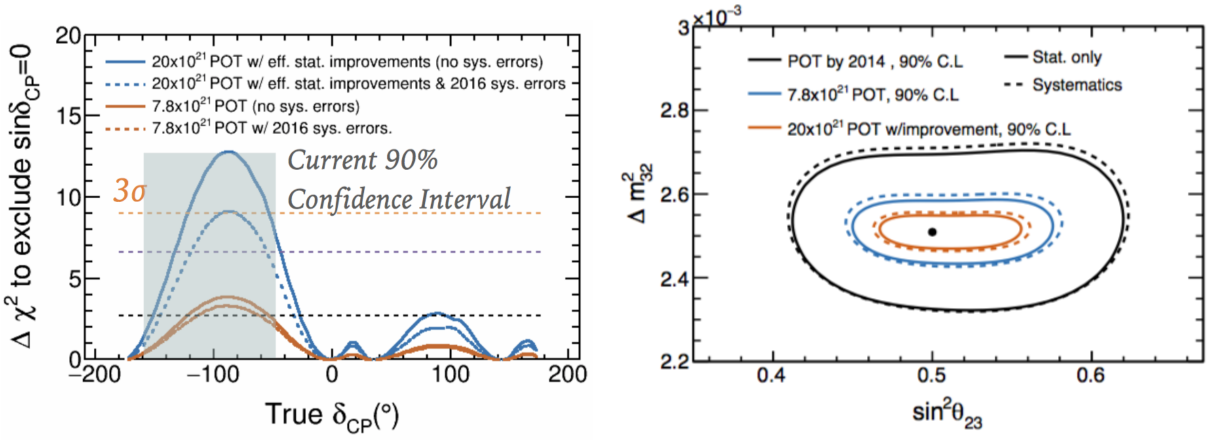


Figure 8: Left: Expected T2K-II sensitivity to $\delta_{\rm CP}$ assuming the mass ordering is not known. Right: Expected T2K-II sensitivity to θ_{23} and $\Delta{\rm m}^2_{32}$.

The updated scientific program also contains measurements of mixing parameters, θ_{23} and Δm^2_{32}, with a precision of 1.7° or better and 1%, respectively. With accelerator and beamline upgrades, as well as analysis improvements, this program, known as **T2K-II**, would occur before the next generation of long-baseline neutrino oscillation experiments that are expected to start operation in 2026.

From Fig. 8 the need for condition #2 is also clear. In order to fully profit of the foreseen additional statistics a better understanding on systematic uncertainties and, in particular, the

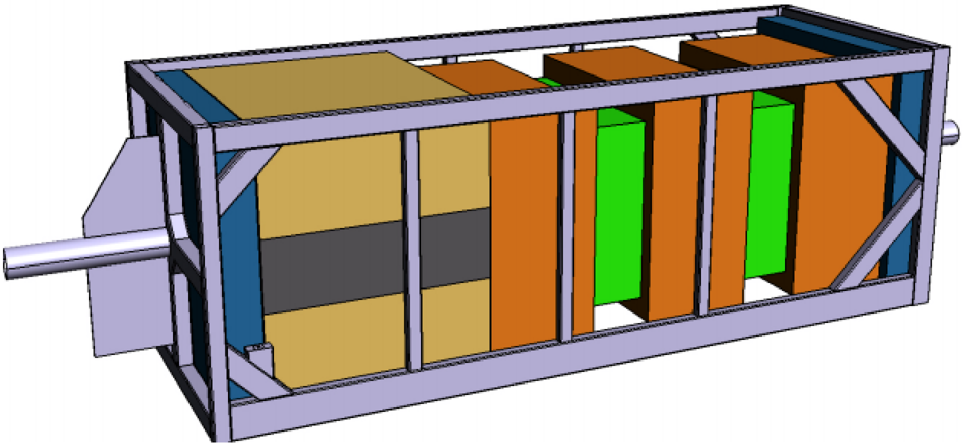


Figure 9: Sketch of the ND280 upgrade project. In the upstream part of the detector (on the left in the drawing) two horizontal TPCs with a high-granularity scintillator module in the middle will be installed. In the downstream part, the tracker system composed of three TPCs (orange) and two FGDs (green) will remain unchanged.

ones related to flux and cross-section systematic uncertainties. The LPNHE neutrino group plans to continue the long–lasting activities in order to reduce systematics on the flux (NA61/SHINE replica target data) and cross-section measurements and modelling. In addition, the T2K collaboration has launched an upgrade project for the Near Detector, aimed at overcoming the known limitations of the current ND280 design that concerns the angular acceptance of the near and far detectors.

Thanks to the cylindrical shape of the tank and to its large size, in fact, Super-Kamiokande has an efficiency in selecting neutrino interactions that is independent on the outgoing charged lepton direction. The geometrical configuration of the ND280 tracker, instead, allows to select with excellent efficiency tracks emitted parallel to the beam direction but this efficiency rapidly degrades with the angle with respect to the beam, being close to zero for $\cos\theta \leq 0.4$ (where θ is the angle between the emitted lepton and the beam). This means that, when ND280 data are used to constrain the flux and cross section uncertainties in the oscillation analysis, the data driven constraints obtained in the forward region are extrapolated to the high-angle and backward regions by using cross section models, naturally bringing additional sources of uncertainties to the oscillation analyses.

To overcome this limitation, an upgrade of the ND280 detector is proposed. The baseline proposal is shown in Fig. 9. It achieves a much better uniformity of acceptance as a function of polar angle, by reconfiguring the geometry with a fully active scintillator detector acting as neutrino target, disposed along the plane including both the beam direction and the magnetic field. The favoured option for this detector is the Super-FGD concept, consisting of small scintillator cubes each read-out by three WLS fibers. Two new TPCs cover the large angles and time-of-flight detectors allow rejection of out of fiducial volume events.

As shown in Fig. 10, such configuration, combined with the existing tracker system, will allow to select with similar efficiencies outgoing charged leptons emitted in any direction with respect to the beam giving a better handle to distinguish among different neutrino cross-section models and to better constrain the parameters in these models. The LPNHE group is currently participating in the optimization of the design for the Near Detector upgrade and is performing studies to investigate the impact of such upgrade on the T2K oscillation analysis. Such studies will continue in the next years and will drive the final design of the upgrade with an installation of the new detectors at J-PARC foreseen in 2021. As it will be detailed in the following of this section, the LPNHE neutrino group will participate in the development and production of the new readout electronics for the new horizontal TPCs.

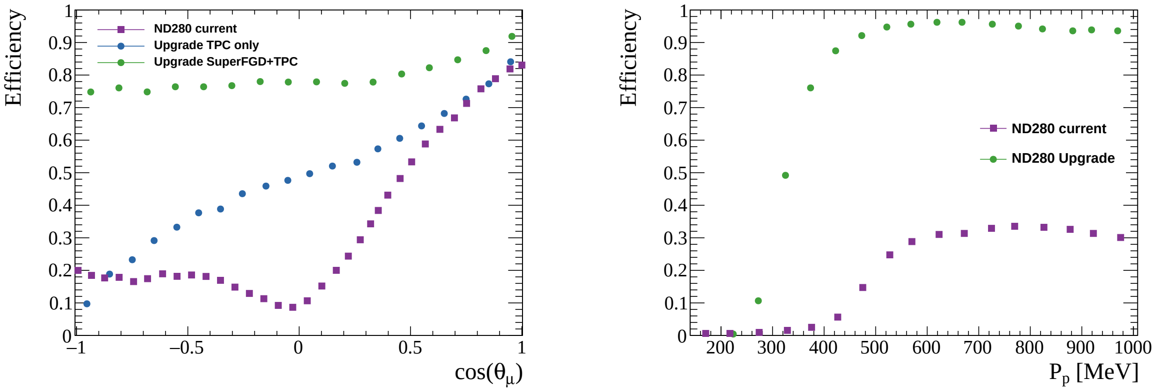


Figure 10: Left: Muon selection efficiency as a function of $\cos\theta$ for the current ND280 detector and for the upgraded Near Detector. Blue points show the efficiency by requiring the muon to enter the TPC while for the green points only the SuperFGD is used for the track reconstruction and particle identification. Right: efficiency to reconstruct protons as a function of outgoing proton momentum for the current and upgraded ND280 configurations.

Finally, as to the condition #3, the T2K and NOνA collaborations plan to perform a combined oscillation analysis by 2021. This combination will provide the best constraint on the mass ordering and on CP violation. T2K and NOνA, while being sensitive to the same oscillation parameters, have different baselines (295 versus 810 km) and different neutrino energies (600 MeV versus 2 GeV). A proper combination of the two experiments is then mandatory to obtain reliable measurements of these fundamental parameters of the neutrino mixing. This will require a large amount of work in order to unify the neutrino flux prediction, to define a common model for the neutrino cross-section, able to describe neutrino cross-sections in the whole energy range of interest, from 300 MeV to 3–4 GeV and finally to identify a common way to propagate the constraints from the near detectors to the far detectors. In T2K several near detector samples are used to constraint the flux and cross-section model while in the case of NOνA they have identical detectors and they directly use the reconstructed energy spectra at the near detector to obtain the predicted energy spectra at the far detector. The two approaches have strengths and weaknesses and a common way of propagating uncertainties will have to be developed in order to combine the oscillation analyses. Common working groups are being established between the two collaboration and the LPNHE neutrino group plans to be involved in this effort.

Continuation of our group involvement in the T2K and T2K-II projects would require a financial support of about 50 k€ per year.

3.2 Hardware involvements in the ND280 upgrade project

Within the ND280 upgrade project the LPNHE-neutrino group will contribute to the development of readout electronics for the new Horizontal TPCs (HTPCs). This project is described below in more details.

The readout system of the HTPC is conceptually very similar to that of the existing TPCs [17]. Differences, technical improvements and simplifications are outlined below.

3.2.1 Readout architecture

The architecture of the readout system of the HTPC is schematically shown in Fig. 11. It is based on the replication of the modular structure used to read out each Micromegas detector module. The front-end electronics is composed of two types of electronic boards: the Front-End Cards (FEC) capture the analog signals of the pads of each detector module and convert the acquired samples in digital format using a fast multi-channel analog to digital converter (ADC). Elementary data processing such as baseline offset correction, zero-suppression and temporary storage is performed by the Front-End Mezzanine card (FEM) which is connected to the number of FECs required to read out one detector module. In order to minimize the degradation of the highly sensitive detector analog signals and avoid the high cost of cables, the FECs and the FEM are directly mounted at the back of detector modules, as it is done for the existing TPCs. The data of each detector module is transported outside of the detector magnet via an optical fiber to a back-end unit that aggregates the data of multiple modules and distributes the global clock and common trigger signal to the front-end electronics using the return path of the optical link. Each back-end unit is connected via a standard Gigabit Ethernet point-to-point link to a control PC that bridges the HTPC readout system to the global run control and data acquisition system of the ND280 detectors. Alternatively, the back-end units may be connected directly to the local area network of ND280 provided that they run directly the data acquisition programs based on the MIDAS framework used by the experiment.

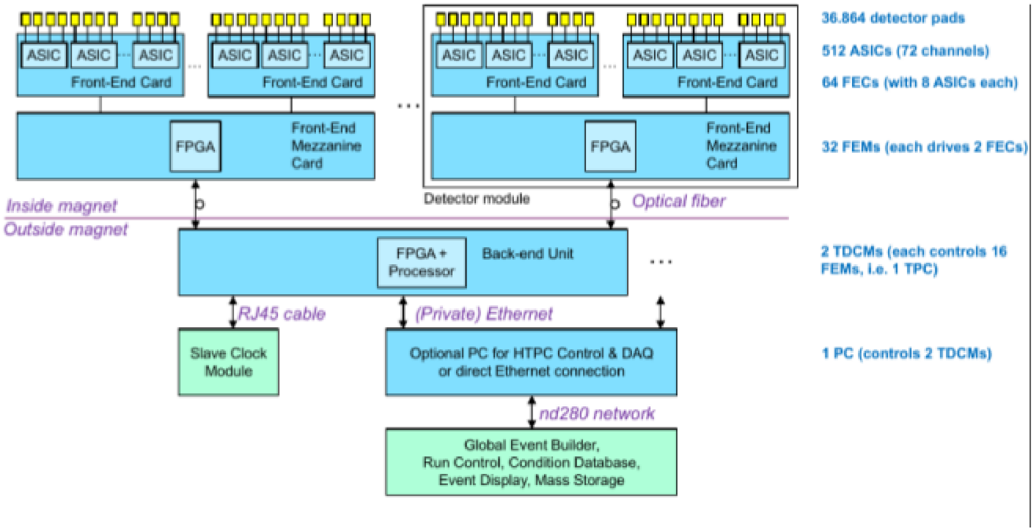


Figure 11: The architecture of the readout system for the new HTPC.

3.2.2 Front-end electronics

Readout ASIC

Several options have been considered for the readout ASIC of the HTPC: the AFTER chip [21], designed for T2K and used in the current TPCs and FGDs, its successor, the AGET chip [19], or a derivative, the DREAM chip [20]. However, the improvements and additional features of these newer devices would not bring any real benefit compared to the original AFTER chip given the requirements of T2K. Therefore, we propose to build the readout system of the HTPC around the AFTER chip, which is a proven solution. The remaining stock of encapsulated and tested AFTER chips is 600 units (i.e. 50,000 channels) which is expected to be sufficient for the project. If required, more chips could be produced, but extra time and resources would be needed in that case, and the obsolescence of the plastic encapsulation used for the original AFTER chip is an issue that would need to be solved.

Front-End Cards

The FECs support the AFTER chips that amplify detector pad signals and sample them in an analog memory (511-bucket switched capacitor array) which is digitized by a commercial 25 MHz 12-bit ADC when a trigger occurs. Assuming that resistive Micromegas detectors are used, the number of channels per detector module will be reduced compared to the current TPCs (e.g. from 1728 pads to 1152 pads) and the anti-spark protection circuit currently used on every channel will no longer be needed. We expect that the corresponding reduction in channel count and board area for passive components will allow a sufficient reduction of the size of the FECs to mount them parallel to the detector sensitive plane instead of the significantly less compact perpendicular orientation used on the existing TPCs. We also plan to double the number of AFTER chips per front-end card from four to eight, so that only two 576-channel FECs per resistive Micromegas detector module will be required instead of the six 288-channel FECs used for the metallic Micromegas detectors of the current TPCs.

Front-end Mezzanine Cards

Each FEM performs the data aggregation of the two FECs of a detector module. A mid-range FPGA, coupled to a memory buffer and ancillary logic, implements all the required functions and interfaces to the back-end electronics via an optical fiber link. Compared to the FEM of the existing TPCs, the FEM for the HTPC controls two FECs (double density) instead of six and no longer includes a dedicated microcontroller and CANbus slow control network. This simplifies design, development and maintenance. Current, voltage and temperature monitoring on the new FEM is controlled by the local FPGA and monitoring data is time multiplexed over the optical link along with detector data. Assuming that the two HTPCs are composed of two end-plates of eight detector modules each, the corresponding readout system comprises 32 detector modules, 32 FEMs and 64 FECs.

3.2.3 Back-end electronics

The back-end electronics is composed of several units which control multiples FEMs and interface to the data acquisition system of the experiment through an intermediate PC, or directly. Each back-end unit is an electronic board composed of a commercial System-On-Module plugged on a custom made carrier board. The carrier board also includes a plurality of optical transceivers to connect to the front-end. The physical layer of the optical links may be placed on a mezzanine card that plugs on the carrier board of the back-end unit. This structure is adopted for the general purpose "Trigger and Data Concentrator Module" (TDCM) currently under development for multiple projects, possibly including T2K. A newer improved version could also be built. The current TDCM uses the powerful Mercury ZX1 module [22] from Enclustra based on a Xilinx ZYNQ FPGA that integrates a multi-core 800 MHz ARM processor. The TDCM supports up to two 16-optical port mezzanine cards. A TDCM with only one 16-port optical link mezzanine card would be adequate to read out each HTPC, i.e. the complete system would require two TDCMs. The primary 100 MHz clock and the common trigger signal is provided to the back-end modules by the Slave Clock Module (SCM), a board currently used in ND280.

3.2.4 Control and data acquisition software

Two options are being considered for the control and data acquisition software. In the first scheme, which is unchanged compared to the existing TPCs, the processor of the back-end units execute a simple "bare-metal" command interpreter program and an intermediate PC running the MIDAS framework performs the translation between the global data acquisition system and the HTPC sub-system. In the second scheme, which is currently deployed in the FGD readout, the processor of the back-end units run the Linux operating system and execute MIDAS processes locally so that the connection of the HTPC to the common data acquisition of the experiment is made directly. There are pros and cons to each scheme.

3.2.5 Ancillary services

Because the HTPC will have less channels than the existing TPCs, power requirements will be reduced. Instead of bringing a high current 5V supply to the front-end modules, we plan to transport a higher voltage, e.g. 12 V or more, over cables of significantly smaller cross section and perform efficient power conversion locally using DC/DC converters. Finding a solution usable in a 0.2 T magnetic field needs further studies. We anticipate that the total power consumption of the front-end electronics of the two HTPC will be 640 W (e.g. 4 V x 160 A). Because the front-end electronics is placed in a confined space, water cooling is necessary. Using bi-directional optical transceivers instead of optical transceivers that require different fibers for the transmission and reception path allows halving the number of optical fibers.

3.2.6 Test-benches

Test bench for the production of the Front-end Cards

The role of this test stand is the quick validation of every FEC at the end of the assembly line: verification of all input channels, assessment of the noise level and measurement of the crosstalk level between neighbouring channels. Calibration pulses will be injected with the built-in pulser of the FEC. A custom PCB will make a capacitive load representative of a Micromegas detector. The test bench will also consist of a validated FEM and a portable DAQ computer. A user-friendly interface will allow a non-expert technician to run a pass or fail test at the production factory. Detailed tests and analysis of eventual defects will be performed by the designers of the FEC in a laboratory environment.

Test bench for the production of the Front-end Mezzanine Cards

This test stand is required for the validation of every FEM at the production site. All the analog and digital functions and interfaces of this card have to be tested. Using the appropriate dedicated software on a small DAQ computer, a technician at the board factory will run a pass or fail test. Deeper analysis will be conducted by the designers of the FEM if that is needed.

To conclude on this part, the LPNHE directorate has already provided some technical support for the ND280 upgrade project. In particular, with the help of electronics engineers the LPNHE group will develop a new Front-End-Card (FEC) which will be used as a first element in the signal read-out chain for resistive Micromegas in the new horizontal TPCs. This work will be performed in close collaboration with the TPC electronics project leader – Denis Calvet (CEA). In total, 80 FECs will be produced, including spares. A new suspension system for the horizontal TPCs will also be developed with the help of mechanical engineers. We also plan to contribute to the new DAQ system for the horizontal TPCs. The estimated cost of this project is about 150 k€ (to be refined in the future and to be approved by the IN2P3 directorate). As already discussed during the last LPNHE meeting on resources and manpower, the technical support from electronics and mechanical engineers will be needed till the installation of the upgraded detector in 2021.

Moreover, after about ten years of operation, the magnet power supply (our group is responsible for) requires a regular maintenance by the production company. Some dedicated resources ($\sim$ 15 k€) should be allocated for that at least once per two years.

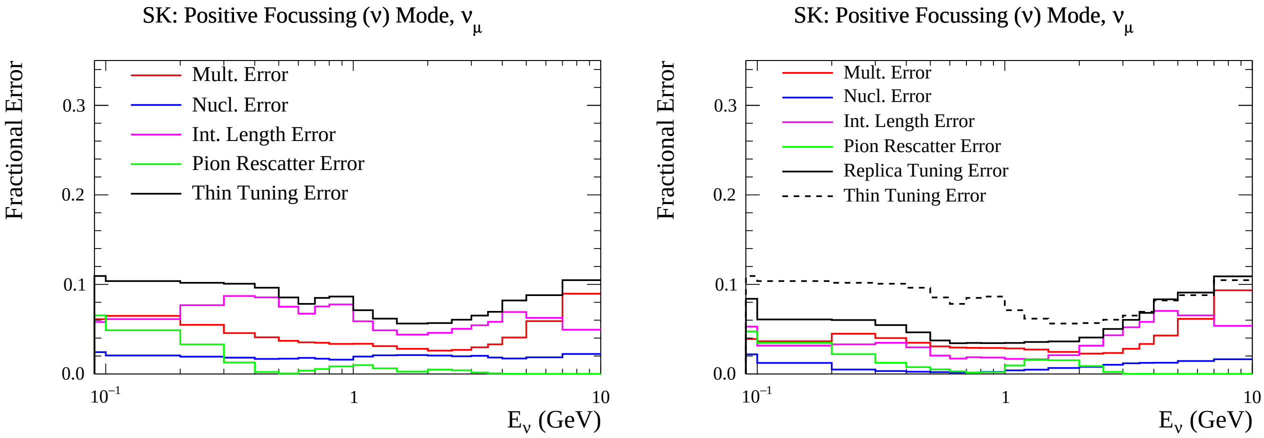


Figure 12: The hadron interaction model uncertainties evaluated on the SK flux prediction. The uncertainties have been calculated for the flux constrained with either purely NA61/SHINE 2009 thin-target data (left side), or using a combination of NA61/SHINE 2009 thin-target and replica-target data (right side, denoted as the replica tuning error).

3.3 NA61/SHINE beyond 2020

During the recent 'NA61 beyond 2020' workshop [7] the importance of hadron production measurements for on-going and future neutrino experiments was strongly emphasized by all neutrino physics speakers. Many accelerator and atmospheric neutrino experiments expressed interest in new additional thin-target measurements. These range from very low beam momenta up to 120 GeV/c.

Published NA61/SHINE thin-target measurements [8, 9] [NA61/SHINE-3,10] have been crucial for T2K to reduce (anti-)neutrino flux uncertainties down to $\approx 10\%$, and further improvements - by a factor of two (see Fig. 12) - are expected soon [10], as the T2K replica-target results [NA61/SHINE-1,8] are added to the T2K's flux model. Moreover, additional improvement is expected with the 2010 replica target data [5], in particular, the uncertainty in high neutrino energy region because of significant improvement of the knowledge of the kaon yield from the replica target data.

The SPS beam group has discussed constructing a tertiary hadron beam-line for beams at very low momenta ($<$ 12 GeV/c). Measurements with these low-energy particles could be very important for future high-precision T2K physics. The low momentum (less than 12 GeV/c) hadron production data are also useful for improvement of the atmospheric neutrino flux prediction for future neutrino experiments, such as Hyper-K and DUNE.

The J-PARC Main Ring beam power is planned to be increased from the current 475 kW to 1.3 MW and some upgrades of the neutrino beam facility are also planned. The neutrino production target will be upgraded by enhancing the cooling capability by increasing the pressure of the cooling helium gas and re-optimization of its titanium window geometry while the shape of core graphite target part will not be changed. The same J-PARC neutrino beam-line will also be utilized for the Hyper-K experiment.

For T2K-II and Hyper-K a reduction of the total flux uncertainty down to 3–4 % is desired. The major uncertainty in the replica target tuning is still hadron production. Further improvement of the hadron production data can be expected from the following measurements:

- Improved measurement of hadron production with the T2K replica target,
- Hadron production with low momentum beams.

Moreover, a new design of the neutrino production target is being discussed. Motivating the new target is an increase of the neutrino flux while reducing the wrong sign neutrino flux for better significance of neutrino CP violation measurements.

T2K is considering hybrid and alternative target materials – e.g. Super-Sialon ($Si_3N_4Al_2O_3$), which has a density of 3.2 g/cm^3, 1.8 times larger than the current graphite target – for high-power operation in the T2K-II/Hyper-K era. Hadron production measurements with these new target materials are a priority for the early post-LS2 NA61/SHINE operation. Whether new measurements with the existing T2K replica target are needed will be concluded after introducing the NA61/SHINE 2010 replica-target results [5] in the T2K beam simulation. The design of new targets for the future high-intensity long-baseline neutrino experiments (DUNE and Hyper-K) is in progress now. Prototype long targets could possibly be available in 2022 and beyond.

Additional tracking detectors will improve the precision of long-target measurements, especially for the very long targets for DUNE. The target could be surrounded by a set of tracking detectors to pinpoint low-angle tracks from the upstream end of the target.

A detailed document with an updated scientific program has been recently submitted by the NA61/SHINE collaboration to the CERN SPS [NA61/SHINE-12] for evaluation and beam request after the LS2. Participation in this NA61++ program would require a financial support of about 15 k€ per year.

3.4 Hyper-Kamikande project

On the longer term, two next-generation long-baseline neutrino oscillation experiments are planned to start taking data in the second half of 2020s [23]: **DUNE** in the US and **Hyper-Kamiokande** (Hyper-K or HK) in Japan. The two experiments have the common goals of measuring the δ_{CP} phase and the mass ordering but using different experimental techniques (LAr vs Water Cherenkov), different neutrino energies ($E_\nu \sim$2 GeV for DUNE and $E_\nu \sim$600 MeV for HK), and different baselines (1300 km for DUNE and 295 km for HK), hence being highly complementary.

DUNE, thanks to its longer baseline, will provide a clean determination of the mass ordering. Both experiments expect to discover CP violation at more than 5σ (3σ) for the 50% (75%) of the values of δ_{CP} as shown in Fig. 13. An independent comparison of experiments' sensitivities can be found in a recent study [24].

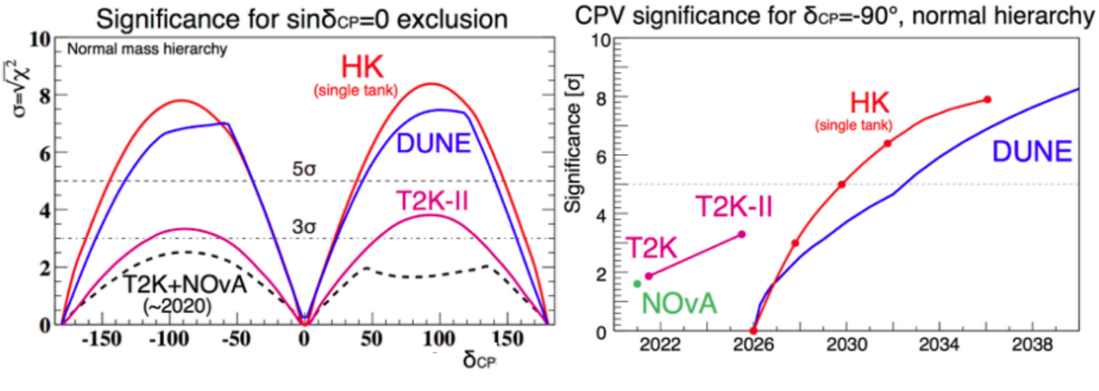


Figure 13: Left: Expected sensitivity to exclude sinδ_{CP} =0 as a function of the true value of δ_{CP} for T2K+NOνA, T2K-II, DUNE and Hyper-K after 10 years exposure. Right: Expected sensitivity to exclude sinδ_{CP} =0 if δ_{CP} = -π/2 and the ordering is normal as a function of time.

While we believe that the successful construction and exploitation of both experiments is mandatory for the neutrino community, it has recently become clear to the members of the LPNHE-neutrino group that the Hyper-Kamiokande project is the most attractive option in order to pursue our scientific activities.

The already proven water Cherenkov technology represents a realistic approach. The larger size of HK makes it the most sensitive experiment to rare events such as the proton decay or neutrinos from supernova explosion. Finally, our past, on-going and future contributions to the T2K and T2K-II projects are important investments and make it rather natural to continue with HK.

The HK project is well advanced and has good chances to be approved by the Japanese government in the nearest future. Full participation in the HK experiment will also open the possibility to enlarge our group experience by studying also solar, atmospheric, supernovae neutrinos and by performing combined analyses of accelerator neutrino and anti-neutrino data with measurements of (anti-)neutrinos from natural sources.

The advantage of such staged and incremental proposal, is that, while getting full experience with a precision neutrino oscillation experiment like T2K and T2K-II, they allow us to work on beam design studies, detector R&D's and physics potential at each stage.

Hyper-Kamiokande [25] is a proposed next-generation general purpose neutrino detection experiment whose broad physics programme covers many areas of particle and astroparticle physics. Based on the proven technology of (Super-)Kamiokande, its much larger detector volume and additional improvements in key areas like photosensors and near/intermediate detectors make HK a straightforward yet powerful extension of the very successful Japan-based neutrino programme.

HK consists of an underground water Cherenkov detector that will be located about 8 km south of the Super-Kamiokande in the Tochibora mine with an overburden of 1750 m.w.e. The detector will be cylindrical (60 m high and 74 m in diameter) and have a fiducial (total) mass of 187 (260) kton, making it more than 8 (5) times as large as its predecessor. HK will use 40,000 photomultiplier tubes (PMTs), thus reaching the same 40 % photocoverage as SK, and benefit from newly designed high-efficiency PMTs.

Construction is expected to take eight years, with start of operations planned for 2026. The option to add a second detector soon afterwards is actively being explored.

While the second detector could be located in Japan at the same site as the first one, the alternative possibility of building the second tank in Korea was explored in a white paper published recently [Hyper-Kamikande-1]. In addition to sensitivity improvements for the long-baseline experiment, the Korean candidate sites offer a higher overburden (and thus lower spallation backgrounds) than the Japanese HK site, which would increase sensitivity of low-energy rare event searches like solar or supernova relic neutrinos.

A new 50 cm PMT model, the Hamamatsu R12860-HQE, was developed for HK. It is based on Hamamatsus R3600 PMT used in SK, but includes a box-and-line dynode and several other improvements. As a result, this new model offers better timing resolution and twice the detection efficiency due to improvements in both quantum efficiency and collection efficiency. Work to reduce the dark noise rate and design new PMT covers for pressure resistance is currently ongoing.

In addition to this baseline design, R&D on alternative photosensor options like hybrid photodetectors, LAPPDs and multi-PMT modules is ongoing.

We are currently investigating possible contributions to the HK project. Discussions are currently on-going with our colleagues from LLR and CEA is order to define a common french hardware contribution. In particular, there is some interest in using the existing Memphyno installation at APC for performing underwater tests of the multi-PMT modules developed in Europe. There is also a possibility of contributing to the development of electronics for the PMT readout based on a chip designed by the Omega laboratory.

At this stage, the evaluation of required resources to participate in the Hyper-Kamiokande project is not possible.

Let us stress once again that a significant involvement in the ND280 upgrade can be considered as a hardware contribution to the future HK project.

With this document we request an approval from the LPNHE Scientific Council of the described scientific strategy.

4 Publications and Conferences

Over the last five years T2K and NA61/SHINE publications were our main scientific production. For several of these papers the group members were the principal authors.

4.1 T2K

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