Załącznik nr 2b do wniosku o wszczęcie postępowania habilitacyjnego
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Summary of professional accomplishments

Contents

1 Personal data

Name: Justyna Łagoda

2 Education

1999 : Master of Science in physics, specialization: particle physics. University of Warsaw, Faculty of Physics
Title of master's thesis: *RPC gaseous detectors in the muon trigger system of CMS experiment*
Supervisor: dr hab. Wojciech Dominik
Obtained on: September 22, 1999

2006 : Doctor of Philosophy. University of Warsaw, Faculty of Physics
Title of Ph.D. thesis: *Liquid argon Time Projection Chamber for investigation of neutrino interactions*
Supervisor: dr hab. Wojciech Dominik
Referees: prof. dr hab. Krzysztof Doroba,
prof. dr hab. Henryk Wilczyński
Obtained on: January 9, 2006

3 Employment in research institutes

In reverse chronological order:

2010 – now : assistant professor, National Centre for Nuclear Research;

2007 – 2010 : assistant professor, Institute for Nuclear Studies, post-doctoral fellowship POL-POSTDOC III;

2005 – 2007 : *postdoctoral fellow*, Laboratori Nazionali del Gran Sasso (LNGS), Assergi, Italy, in the framework of *Post-doctoral fellowship for non-Italian citizens* of Istituto Nazionale di Fisica Nucleare;

2004 – 2005 : senior specialist, University of Warsaw, Faculty of Physics;

1999 – 2004 : Ph.D. studies, University of Warsaw, Faculty of Physics.

4 History of scientific work

4.1 Master's thesis and Ph.D. studies

Being an undergraduate student at Faculty of Physics at University of Warsaw, I started to collaborate with the Warsaw group of CMS experiment. My task for the master's thesis was to study behaviour of gaseous detectors called Resistive Plate Chambers in the conditions of heavy irradiation, both through the measurements and the simulation in GEANT framework. The studies were summarized in my master's thesis under the supervision of prof. W. Dominik. The title of the thesis was *RPC gaseous detectors in the muon trigger system of CMS experiment.*

When I decided to start Ph.D. studies, my plan was to continue the work on RPC detectors. During the first year I became interested in the possibility of participation in a novel neutrino experiment ICARUS [1], as a member of freshly formed Polish Neutrino Group, gathering physicists from several institutes in Poland, in particular University of Warsaw and Institute of Nuclear Studies (now known as National Centre for Nuclear Research).

ICARUS detector was a time projection chamber filled with liquid argon, with the read-out through three planes of anode wires, which allow for very precise studies of neutrino interactions. A 600-ton prototype was at that time prepared for the test data taking with cosmic rays. My first task was to design the cosmic trigger, providing as uniform irradiation of the detector as possible, with high statistics of collected signals for all read-out wires, but not too high signal rate. The designed system was constructed and tested by me in Laboratori Nazionali del Gran Sasso (LNGS) in Italy, and then installed on top of the detector and used during the data taking in Pavia in 2001, where I was also doing shifts at the detector. The description of my trigger system is included in the technical note summarizing all used triggers [2].

After the data taking was finished, I worked on detector calibration. I performed visual scanning of collected events, looking in particular for the muon tracks which crossed whole drift length. I used those tracks to measure the drift velocity of the ionization electrons in electric field inside liquid argon, a quantity necessary for proper reconstruction of the events. I participated also in the work concerning the reconstruction of the energy of cascades, and the measurement of the π^0 and η^0 masses as a test of the detector energy resolution.

Both tasks were described in the technical notes [3, 4], and the results were used in ICARUS publications [5, 6].

My further work in ICARUS was related to the study of argon scintillation light, which is used in fast, internal trigger system of the detector. I developed a simulation of production, propagation and detection of the light in GEANT 3 framework, in which the light attenuation in argon, Rayleigh scattering, detector effects related to the construction and efficiency of the photomultipliers mounted inside the cryostat and the internal structure of the detector were taken into account. I compared the results generated by the simulation with the collected data for various configurations of tracks in the detector, obtaining a constant calibration factor for the simulation. The work on the scintillation light was a significant part of my Ph.D. thesis.

Apart from the activities related directly to the ICARUS detector, I worked on the methods of searching for the $\nu_\mu \to \nu_\tau$ oscillations in high energy neutrino beam CNGS (CERN Neutrinos to Gran Sasso). The group I belonged to developed a method to select events with produced τ lepton, which was a signature for the oscillations, using neural network. The multilayer neural network was fed during training process with a set of kinematic variables describing the simulated event (total momentum, total energy, missing transverse momentum and others), together with the information of the identity of the event: the signal was defined as charged current interaction of tau neutrino, while the other neutrino interactions belonged to the background. Such process of so called *supervised learning* allowed to obtain a set of weights for the connections between neurons in the network. The trained network was then tested with a different sample of events. My main task was to study the polarization of the emerging τ lepton and its possible influence on the distribution of the variables used in the selection. The analysis was also performed for the atmospheric neutrino flux, and the results were included in the technical note, my Ph.D. thesis and a publication [7, 8].

My work and the results were many times presented at the collaboration meetings in CERN and LNGS. I'm also a co-author of six ICARUS publications in years 2000-2005.

I defended my Ph.D. thesis entitled *Liquid argon Time Projection Chamber for investigation of neutrino interactions* at the Faculty of Physics in December 2005.

Being a Ph.D. student, I travelled many times to LNGS for visits lasting usually several weeks. I worked with LNGS group on data analysis and development of event selection methods. Thanks to fruitful and successful collaborative work, I was given support when I applied for a post-doctoral position within Italian program of Istituto Nazionale di Fisica Nucleare for foreigners, which I received and started in December 2005.

4.2 Post-Ph.D. period and present scientific activity

4.2.1 Activity related to liquid argon technique Działalność związana z technologią ciekłoargonową

From December 2005 to November 2007 I worked at Laboratori Nazionali del Gran Sasso in Italy as a post-doctoral fellow.

I planned to work on the taking and analysis of the data collected with recently started CNGS neutrino beam. Unfortunately, all the work related to the installation of any new detectors inside the underground laboratory halls was significantly delayed due to an accident, which could be dangerous due to potential environmental consequences (the laboratory is located in a national park). Eventually, the ICARUS detector was installed there after my return to Poland two years later.

Because of that fact I continued the analysis of the old ICARUS data. I was searching for tracks of given characteristics (length and position in the detector), which were then used to measure the energy loss for the ionization along the track and to compare to the energy used for production of scintillation light.

During the post-doctoral stay I started to work on another topic, namely the Monte Carlo simulation of neutrino interactions. I was working on the improvements in the code of GENEVE generator, which allowed to simulate the interaction of neutrinos with atomic nuclei in the energy range from 100 MeV to several GeV. Thanks to the method used to model the quasi-elastic events, GENEVE allows for very precise treatment of the charged current interaction kinematics, in particular at the energies close to the threshold for muon production, and also for prediction of cross section for interactions with bound nucleons. My activity concerned the rewriting of the code in C++ programming language, reorganization of the structure because of object oriented programming, optimalization of the algorithms and variables, leading to planned inclusion of GENEVE to object oriented Monte Carlo generator GENIE. GENEVE, modernized by me, was then used to simulate the neutrino interactions in the first phase of ArgoNEUT experiment [9], a small liquid argon detector taking data with NuMI neutrino beam. I also participated in the preparation of the ArgoNEUT prototype built to study ionization and scintillation light production in argon.

After return from Italy, I worked mainly for T2K experiment. Still, I remained the member of ICARUS collaboration, participated in the tests of the read-out electronics for the detector and data taking and continued to select CNGS neutrino interactions. My involvement in ICARUS was significantly reduced in 2013, when I became the NuMu Analysis Group convener in T2K experiment, which is described in the next Section.

In years 2008–2014 I participated in the LAGUNA and LAGUNA-LBNO, European projects dedicated to studies of possibilities and advantages related to construction of a huge neutrino detector in Europe. The first of the projects was focused on the selection of the best place to build the detector (one of considered locations was in Polkowice-Sieroszowice mine in Poland), while the second one was devoted to the methods of searching and studies of the $\nu_\mu \to \nu_e$ oscillations for the finally chosen location in a mine in Finland, where the neutrino beam from CERN could be measured. Among considered detector techniques, there was a project of detector containing several tens of kilotons of liquid argon. My work concentrated on the selection of neutrino interaction with production of τ lepton. The leptonic decay of τ to an electron was one of the main sources of background for the forementioned oscillation channel in such configuration of the experiment. The results of my work were shown at the plenary collaboration meetings and were included in the final report from the project [10, 11].

4.2.2 T2K experiment

From 2007 till now I'm a member of T2K collaboration, an international group of physicists studying the neutrino oscillations with the infrastructure located in Japan. My contribution to this project can be divided into three stages, related to different character of my work: 1. preparation of the experiment, 2. study of the external background, 3. coordination of NuMu Analysis Group.

In years 2007–2010 (stage 1) the experiment was being prepared to start. The elements located in the J-PARC laboratory in Tokai (Japan) were built: the neutrino beamline and two near detectors, one located on the beam axis, and one at the angle of 2.5 degrees (off-axis, same as Far Detector). I was involved in the building of the off-axis Near Detector, called ND280. It is a multi-purpose magnetized detector, incorporating several subsystems, in which various detection techniques are utilized, in particular the scintillation light [12].

Polish groups were involved in the project and building of Side Muon Range Detector (SMRD), consisting of flat scintillator planes located in ND280 magnet yoke [13]. This system is dedicated to detect muons escaping the central part of ND280 and to measure their momenta by range. SMRD is also an important part of the cosmic trigger system, used in the calibration process and tests of the reconstruction, but also providing control samples for estimation of some systematic errors.

In years 2007–2010 I received a POL-POSTDOC III funding for the preparation of SMRD.

The SMRD scintillator planes are read-out by modern solid-state photodetectors: Multi-Pixel Photon Counters (MPPC) [14]. Such photodiodes are very sensitive to the temperature, on which the gain and dark noise depend, so it was necessary to design a temperature monitoring system in the magnet. That was my first task: using the provided simulations of temperature distribution inside the magnet I estimated the minimal required number and locations of the temperature monitors, taking into account the limitations from read-out electronics. I participated in the tests of MPPC photodiodes, in which their individual optimal working voltages were found (the voltages are kept in a database and provided to each photodiode automatically) and the damaged MPPCs were discarded.

In parallel to the pure hardware work, I participated in the preparation of the detector simulation. In 2008 I started to work on the simulation of one of ND280 cosmic trigger systems, which is based mainly on SMRD subdetector and requires specific configurations of signals in SMRD counters. The trigger allows to select particular directions and positions of muons, to ensure optimal irradiation of the inner parts of ND280. The software I wrote takes into account all the requirements for the SMRD signals: the amplitudes, time window and correlations, and allows to select cosmic muon tracks of given configurations, both from the simulation and data. In 2009 the program was enriched by the simulation of other subsystems used in the trigger and in 2010 it was included in the official software of the experiment.

Together with a colleague from Warsaw group, I also prepared a simulation of cosmic muons for ND280, using the GEANT framework. I used it to generate the sample of cosmic muons, which was then provided for the collaborators from other T2K groups. The simulation became soon a part of official software and the task of producing new larger simulation samples was passed to younger members of the T2K collaboration as a service task.

Using the simulated cosmic muons flux and my trigger simulation I studied the rates of the cosmic muons in various configurations of the trigger and prepared a matrix of the scaling factors, which decreased the rates of the cosmic events to the values acceptable by the read-out electronics and also optimalized the distribution of events in the inner ND280 subsystemts. Using the matrix, the Electronics Group developed the configuration of the cosmic trigger which was then used during the data taking.

In 2009 I participated in building of SMRD detector in Japan. I took part in every stage of the construction: from the assembling of several counters into a module, equipping the module with photodiodes, temperature monitors and cables, testing of the modules with cosmic rays, to the installation of the modules inside the magnet. During several next visits in 2009 and 2010 I participated in the tests of the complete SMRD detector which collected cosmic rays events at that time, mapping of the electronic channels and improving of the temperature monitors read-out by installation of additional electronic elements.

In 2010 the complete ND280 detector began to take data, both the beam neutrino interactions and the cosmic rays events, which were used for testing and calibration (here my results concerning the predicted rates and distributions of the muons were used). I analysed part of the cosmic data, obtaining angular distributions and relative rates of muons in different configurations, and compared them to the data. The agreement was very good, which meant that both the process of the simulation and the understanding of the detector performance were correct. I was also working on the tests of the track reconstruction in SMRD, finding some errors related not only to the reconstruction itself, but also to the modelling of SMRD geometry and the scintillation light detection in the simulation.

Results of my work on the SMRD subdetector, cosmic trigger, simulation and analysis of the cosmic rays were many times presented at the meetings of the ND280 Group.

I continued to work for the SMRD group in 2010, when I supervised a student from Faculty of Physics at University of Warsaw, who prepared his master thesis concerning the efficiency of SMRD counters [15] within Warsaw Neutrino Group.

The second stage of my activity in T2K began in years 2010–2011, when I started to collaborate with the ND280 NuMu Analysis Group. It is a crucial group for the experiment, as it works on the measurements of the main beam component: muon neutrinos and antineutrinos in the ND280 detector and on the estimation of systematic errors related to the detector and reconstruction. The measurements are then used in the oscillation analysis to reduce the systematic uncertainties related to the knowledge of the neutrino flux and cross sections for neutrino interactions. Thanks to that, the sensitivity of the experiment is significantly improved. The algorithms of selection and methods of estimation and propagation of systematic errors, developed by NuMu Analysis Group, are used in the measurements of the cross sections in ND280 as well.

My first contribution to the activities of NuMu Analysis Group was related to the studies of the external background for the neutrino interactions in ND280 detector. Such background can originate from cosmic rays or beam neutrino interactions in the surroundings of the detector. The near detectors are located in a 30-m-deep pit, open from the top, dug in soil and equipped with concrete walls and other internal constructions (stairs, pillars, floors).

I performed the first estimation of the background due to the cosmic rays in 2010, when the track reconstruction software in ND280 was still in the testing stage. Therefore the estimation was done both for reconstructed tracks and the signals from single SMRD counters, which were recorded out of beam bunch time. In the latter case, I compared the rate of the signals in data with the predicted rate of signals induced by cosmic muons, dark MPPC impulses and electronic noise. Both methods gave consistent results and showed good agreement between data and predictions [16].

The other source of the external background is related to the interaction of the beam neutrinos in the surroundings of the detector. It is impossible to focus the neutrino beam in the same way as a beam of charged particles, therefore the neutrino beam is always relatively wide (thanks to that fact one can use the off-axis effect, where the neutrinos emitted at some angle with respect to the beam axis produce narrower energy spectrum) and irradiates quite big area around the detectors. Different than for the accelerator beams, the neutrino beam is not inside a vacuum pipe. Therefore, the soil around the pit and the concrete used for the pit construction, having large mass, are the target for the interactions of the neutrinos and the products of those interactions can enter the detector. In case of charged particles, an ideal detector should recognize them by checking the starting point of a reconstructed track, but the reconstruction errors or inefficiency of the detection cause that one cannot reject all such events. Additionally, both in the neutrino interactions and during the propagation of the interaction products through the soil many neutral particles are created, which can then reinteract in the detector and produce charged particles; such events are indistinguishable from neutrino interactions inside the detectors. Therefore it was necessary to develop a dedicated simulation of the interactions in soil, to estimate the contribution from the false signals coming from external interactions in the samples of selected events in the detector which were used in physics analysis. Also, the checks of the agreement between such simulation and the data were important; one can use the charged particles coming from the outside for that purpose.

I started to work on the simulation in 2011. The first urgent stage was to find the optimal size of the volume, in which the interactions would be simulated, and the size of the angular sector of the beam. This was due to the technical solution used in T2K to simulate the neutrino interactions: the predicted flux of the incoming neutrinos is calculated by the Beam Group for a plane of given size and located at a given distance from the neutrino source. At that time, the flux predictions were available only for the planes located just before the detector which were inappropriate for this kind of simulation.

Together with a colleague from Warsaw Group I used the existing planes to extrapolate the neutrino directions back to the production point. Thanks to that we were able to estimate approximate neutrino fluxes at any distance between the production point and the detector. Using a simplified model of the interactions we chose the volume optimal for the simulation, taking into account also the amount of time needed to generate large enough number of interactions. The size and position of the chosen plane was provided to the Beam Group which calculated the neutrino flux for it. From that time on the new flux predictions for analysis updates were always calculated also for the plane we found.

Using the correct flux and generator of the neutrino interactions, I prepared the first samples of interactions outside of ND280 for T2K collaboration. I calculated also the contribution of such interactions to the samples selected in FGD scintillator subdetector (part of ND280) and used for the ND280 data analysis, leading to the suppression of systematic errors in the neutrino oscillation studies. I studied the reasons why the external interactions passed the cuts used in ND280 analysis, which allowed to correct the reconstruction errors and led to decrease of the contamination from external interactions over twice in the next years. I estimated the systematic error on the contribution from external interactions, using the tracks of charged particles entering to the detector through the front (most upstream) wall [17].

The process of the selection for the physics analysis uses a veto for the tracks coming from the upstream part of the detector. I estimated the influence of the false veto, coming from particles produced in external interactions, which pile-up with a proper interaction inside the detector, on the efficiency of the selection.

I performed the studies on the contamination and false veto also for the cosmic rays, using my cosmic simulation and the tracks coming from particles recorded in so called "empty spills". Such events are collected in the trigger mode synchronized with beam arrival time, but when the neutrino beam is not actually present. Using "empty spills" data allows to collect only the accidental cosmic muons and ensures that the behaviour of the detector identical as for the beam neutrino interactions. The background was found to be negligible [18].

The described analysis of the external background is my contribution to T2K analysis and was used in all T2K oscillation results and cross section measurements published after 2012 (items 1–4, 7–10, 13–18 in T2K publication list, attachment 3b). I presented the methods and results of my work many times at the meetings of NuMu Analysis Group and the main ND280 Group. The analysis is updated for the new data and after major changes are introduced into the simulation of the interactions, neutrino flux or reconstruction algorithms. The update is still my task in NuMu Analysis Group, except for the pile-up correction, which was assigned to other members of the group.

In 2013 T2K collaboration observed for the first time the appearance mode in the oscillation, which means observation of neutrinos with different flavour than produced [19]. The discovery of $\nu_\mu \rightarrow \nu_e$ oscillations was possible mainly thanks to the improvements in the analysis, both in near and far detectors. My contribution, apart from the activity in the Near Detector analysis described above, concerned also Far Detector analysis. I was one of four internal referees of the technical notes describing a new reconstruction algorithm for the Far Detector, a new method of neutral pions background rejection, and their tests. The new methods passed the review successfully and since that time are used to obtain all oscillation results published by T2K (items 1, 2, 6–8, 11, 14, 15 in T2K publication list, attachment 3b).

In fall of 2013 I got a proposition to become a convener of the NuMu Analysis Group (stage 3 of my involvement in T2K), for the period of two years, which was extended in fall of 2015. Because of the importance for the experiment, the group has three conveners.

The main task of the group, when I became a convener, was the preparation of new analysis in the Near Detector. The improvement of the previous analysis was necessary because of three reasons, described below in more details: introduction of antineutrino interaction samples, changes in the Near Detector software and decreasing of the dominating systematic error in the oscillation analyses.

The observation of $\nu_\mu \rightarrow \nu_e$ oscillations allows to search for the violation of the charge conjugation parity (CP) symmetry in the leptonic sector, which should lead to different oscillation probabilities in this channel for neutrinos and antineutrinos. Because of that fact, T2K collaboration decided to take data with an antineutrino beam, starting in 2014. Therefore, the introduction of the antineutrino interaction sample to the ND280 analysis became necessary. I was supervising the preparation of the antineutrino event selection methods, which were then used for data taken in years 2014–2015 and included to the official analysis in 2015. I performed also the analysis of the external interactions for antineutrino beam.

Just after I became a convener, many significant changes were being introduced in almost all software fields related to the Near Detector: predicted neutrino flux (thanks to new data from NA61/SHINE on the hadron production in proton-carbon collisions [34]), neutrino interaction generation model, detector calibration and reconstruction. While waiting for the data taking with antineutrino beam, I coordinated some of the tests concerning the reliability of the new simulation. I also participated in the tests, finding some errors in the reconstruction of long tracks and related to the incorrect matching of the track segments from detector subsystems.

Due to the changes in the calibration and software, the estimation of the systematic errors had to be redone, with the improved methods. I repeated the analysis of the external background and was also supervising people working on the uncertainties related to FGD subdetector. One of the uncertainties, related to the reconstruction of a short track in a presence of long muon track, was estimated by Ph.D. student from University of Warsaw directly under my supervision. I prepared the event samples and work environment for her, helped her in implementation of scripts and programs and interpretation of the results. I was also a referee of the technical note describing the methods and results of her studies [24].

The third important task of NuMu Analysis Group in years 2014–2015 was the introduction of the neutrino interactions on water. The event samples used so far contained the neutrino interactions in FGD1 subdetector, which consists of plastic scintillator strips only, so the interactions happened mainly on carbon nuclei. Since the Far Detector is filled with water, some of the systematic uncertainties related to the target nucleus could not be reduced by the measurement in the Near Detector and accounted for the dominant contribution to the total systematic error in the oscillation analyses published in [19, 25, 26]. The measurement of the interactions on water in ND280 aimed to constrain this error.

ND280 contains two FGD subdetectors, one is composed of the scintillator layers only (FGD1, which was exclusively used so far in the analysis), and the other one has the water layers interleaved with scintillator layers (FGD2). The addition of the neutrino interaction on water in FGD2 required the preparation of selection methods and estimation of systematic errors, similarily as for FGD1 analysis. Moreover, one had to take into account the possible correlations between errors in FGD1 and FGD2 subdetectors. My contribution concerned the analysis of the external background and the supervision on the work on FGD-related uncertainties.

The improvements included into the analysis during this stage of my work in T2K are summarized in a long technical note (over 170 pages), of which I was the main editor. The note describes all the systematic errors together with the methods of their propagation and the selection of the interaction samples for the neutrino beam events [27]. The selection of samples for antineutrino beam is described in two other technical notes, reviewed by me [28, 29].

The new samples provided by NuMu Analysis Group are gradually introduced to the oscillation analyses and the measurements of the neutrino cross section. The samples for the antineutrino beam were used for the first measurement of $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ oscillations [30]. The samples with the interactions on water were used for the first time in the combined analysis of neutrinos and antineutrinos, being presently (in April 2016) in the final stage.

The NuMu Analysis Group continues the work on the introduction of new samples, taking advantages from the new possibilities available thanks to the forementioned changes in the calibration and software. Among others, the samples with increased angular acceptance (in which the time of flight is used to identify the muons emitted at the angle higher than 90 degrees) are in the final stage of preparation, as well as a separate sample of the antineutrino beam events with single negative pion production, which are enriched in the resonant interactions. In particular, I'm involved in the latter studies, in which I work on the event migration and preparation of the propagation of systematic errors [31].

The samples available for the analysis in not so close future, are the neutrino interactions in P0D subdetector, which is dedicated to detection of neutral pions; and samples of muons coming from the external interactions. The studies performed by me for the external background showed that the muons coming from the outside and penetrating ND280 for the depth of about 2.5 m (passing through the whole length of P0D subdetector) were induced by high energy beam neutrinos, coming mostly from decays of kaons [32]. This region of the neutrino flux was weakly covered by the samples of neutrino interactions in FGD subdetectors used so far. Additionally, thanks to the huge mass of soil, in which the interactions happen, the number of muons coming to the detector from external interactions covering this weakly known part of the energy spectrum is many times higher than in the event samples selected in FGD. Estimation of the systematic errors for such muons, performed by me, shows also that even without the measurement of the soil density, the uncertainties for the external muon samples and for the FGD samples are comparable. The final results of my analysis were presented at the NuMu Analysis Group and recently (January 2016) also at the ND280 conveners meeting and the plenary T2K collaboration meeting. The results are described in two technical notes as well [32, 33].

Except participation in the work of NuMu Analysis Group, since December 2013 I am a member of the Analysis Steering Group, which plans the future analyses and aims of T2K experiment. In years 2014–2015 I was also a contact person between the NuMu Analysis Group and the groups working on the oscillation analyses.

Being a T2K collaboration member, I participated in many shifts at the Near Detector, usually being a so called "shift leader", the person responsible for all the operations in the detector during the shift. Frequently, I was serving also as the expert responsible for the SMRD detector and since 2015 also the expert responsible for all scintillator ND280 detectors using Trip-T electronics.

In years 2008-2011 I participated in the data taking and replacement of read-out electronics in NA61/SHINE experiment [34] which provides the information about the production of hadrons in proton-carbon collision. Such informations are then used in the prediction of T2K neutrino beam.

I also started to work for the planning of the future neutrino projects. I collaborate with the group working on the future detector TITUS, a proposed intermediate detector (at the distance of 2 km from the neutrino source) for the Hyper-Kamiokande project [35, 36]. I prepared a simulation of the external beam neutrino interactions for TITUS, I was also recently chosen for the internal referee of the prepared proposal. I am a member of Hyper-Kamiokande proto-collaboration as well, in which I served as an internal referee of the Chapter on external background for the prepared proposal.

5 Presentation of the scientific achievement

as required by Art. 16 ust. 2 Ustawy z dnia 14 marca 2003 roku „O stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki (Dz.U. nr 65 poz. 595 z późniejszymi zmianami)."

As my scientific achievement I present a monograph entitled:

Improving neutrino oscillation analysis with near detector measurements in T2K experiment

published by Narodowe Centrum Badań Jądrowych, ISBN 978-83-941410-3-5, of which I am the only author.

The work is written in English and the translation of the title to Polish is *Ulepszenie analizy oscylacji neutrin dzięki pomiarom w bliskim detektorze eksperymentu T2K*

The presented monograph describes the analysis of the neutrino interactions in the off-axis Near Detector of T2K experiment, which provides the reference measurement of the neutrino beam near the production point, where the oscillation probability is negligible. The selected samples of beam neutrino interactions enriched in particular types of reactions are used in comparison of data and predictions from the Monte Carlo simulation in the Near Detector. Thanks to that, the parameters used for the predictions of the neutrino flux and modelling of the different kinds of neutrino interactions with matter can be changed in such way, that the best agreement of simulation and data is obtained. The corrected parameters are then used to predict the observations in the Far Detector. Thanks to such procedure, the systematic errors of the experiment are significantly reduced, which is necessary to achieve the sensitivity needed for precise measurements of the neutrino oscillation parameters and searching for the subtle effects of the oscillations related to small mixing angle θ_{13} and possible violation of the charge conjugation parity symmetry in the leptonic sector.

My scientific work in T2K experiment was devoted mainly to the analyses related to the Near Detector. Since the beginning of data taking, I worked on the background coming from the sources outside of the detector (cosmic rays, beam neutrino interactions in the detector pit and the surrounding soil) and the related systematic error. Since fall 2013 I am a convener of NuMu Analysis Group and I am responsible for all the preparations related to the introduction of new samples to the analysis, which allow to decrease the dominant contribution to the systematic error in oscillation analysis, and taking into account new data collected with the antineutrino beam (since spring of 2014). The comparison of neutrino and antineutrinos oscillations is a method to look for the violation of charge conjugation parity symmetry (CP) in the leptonic sector, in which the crucial points are the sensitivity of the experiment and small systematic error, possible thanks to usage of Near Detector, as described in the monograph.

The monograph begins with a short introduction presenting the most important discoveries and questions related to neutrino physics.

In Chapter 1 I present briefly the phenomenological description of the neutrino flavour and mass eigenstates mixing and the mechanism of neutrino oscillations. I give also a review of the recent results related to neutrino oscillations and the results of the searches for the CP violation.

Since the knowledge of the cross sections is crucial in the oscillation studies, I present also the basic informations concerning the interactions of neutrinos in the 1 GeV energy region, which are studied in T2K experiment.

Chapter 2 is focused on T2K experiment and its aims. Three main parts of the experiment are described: the production of the neutrino beam in the decays of focused mesons (mainly pions and kaons) together with the off-axis effect, the set of two Near Detectors and the Far Detector. The idea of the oscillation measurements is also presented, taking as an example the combined analysis of ν_μ and ν_e interaction samples, performed by T2K collaboration in 2014 [26]. The methods of obtaining the data samples and the predictions, as well as the fitting methods used to extract the values of the oscillation parameters and their confidence levels are described. The effect of using the measurements from the Near Detector leading to three-four times decrease of the systematic error is also shown. The Chapter ends with a review of present status and plans of T2K experiment.

The further part of the monograph is devoted to the analysis in the Near Detector, in which I participated both as a person performing part of the analysis and as the coordinator of the working group.

Chapter 3 presents briefly the structure of the off-axis Near Detector (called ND280), and in particular the elements which are used in the described analysis. It contains also the basic information on the detector calibration and reconstruction methods, allowing to understand what kind of informations are available for the analysis.

Chapter 4 presents in details the contribution of the Near Detector to the oscillation analysis. It contains the description of the three neutrino events samples used in the previous analysis shown in Chapter 2, and of the new samples, where my participation was more significant (larger contribution to the analysis itself and the coordination of work of other members of NuMu Analysis Group).

The charged current interactions of muon neutrinos (or antineutrinos) are selected in scintillator detectors FGD and identified via the measurements of the energy loss of the leading particle in gaseous Time Projection Chambers. The inclusive sample of the interactions is then divided into subsamples enriched in particular type of reaction and covering different regions of parent neutrino energy. Such division allows in particular to better fit the parameters used in the modelling of various interactions (quasi-elastic, resonant, coherent, deep inelastic and proposed multinucleon).

The division method is based on the presence and multiplicity of the pions or on the multiplicity of the tracks in a given event. I analysed the reasons of the migration of the events between the subsamples, which allowed to plan the improvements in the reconstruction or selection for the future analysis.

Chapter 4 includes also the review of detector systematic effects, which can affect the selected samples. The estimation of the errors is based on the comparison of data and simulation for control samples, which have the kinematical parameters as similar to the main samples, as possible. The details of the error estimations are not presented (except for the external bacground, which was analysed exclusively by me), only the brief description of control sample and observed differences between data and simulation is given. The differences are then propagated, which means that the effect on the final number and distribution of the events is estimated, leading to the calculation of the total systematic error on the sample.

The momentum and angular distributions of the muons, together with the error covariance matrix are used in a multidimensional fit of the Monte Carlo simulation to the collected data. A short description of such fit is also included in Chapter 4, togerher with obtained systematic error for the most recent T2K oscillation analyses: the disappearance of muon antineutrinos (announced in 2015, [30]) and combined oscillation analysis of muon and electron neutrinos and antineutrino (prepared for publication in 2016).

Chapter 4 ends with review of plans concerning further improvements to Near Detector analysis, which are coordinated by me. It includes the studies of the improvements in purity of the already existing subsamples by using additional detector information; searching for methods to decrease the detector systematic errors, but also introduction of new samples which can provide new information (one of such samples, studied by my, is described later).

Chapters 5–7 present more closely that part of the present and future Near Detector analysis, which was prepared by me only and is related to the external background from the interactions of T2K beam neutrino outside of the detector and to the cosmic rays.

Chapter 5 contains the description of the simulation of the beam neutrino interactions outside of the Near Detector. The particles produced in such interactions can enter the detector and distort the measurement of the interactions inside the detector itself, so the proper prediction of such events is very important. The simulation was prepared and performed by me, for the first time in 2011–2012, and since then it is included into official analysis software of the experiment. The basic informations about the particles produced in the surroundings and entering the detector are also provided.

The estimation of the external background in the selected samples described in Chapter 4 is shown in Chapter 6, together with the evaluation of the related systematic error. This Chapter contains also the estimation of the cosmic ray background which is found to be negligible.

Chapter 7 presents my idea to use the muons coming from the interactions of beam neutrinos outside of the detector as the additional source of the information about the neutrino beam. Such incoming muons were produced mostly by neutrinos from the high energy tail of the spectrum, which originated from decays of kaons. The kaons are also the main source of beam contamination from intrinsic electron neutrinos, which are the background to the searches of oscillations in $\nu_\mu \rightarrow \nu_e$ channel, so the information about them is very valuable. I presented the selection of the external muon samples, both for neutrino and antineutrino beam. The samples are heavily enriched in the kaon component in comparison to the samples presently used in the analysis. I estimated also the systematic error for those samples.

Finally, Appendix A shows how my idea of the simulation of the external interactions can be used in the design process of a new detector TITUS, which in the future is supposed to further decrease the systematic errors in the Hyper-Kamiokande project.

References

[1] S. Amerio *et al.*, "Design, construction and tests of the ICARUS T600 detector", Nucl. Instrum. Meth. A 527 (2004) 329.

[2] F. Arneodo *et al.*, "An external trigger system for the ICARUS T600 test", ICARUS-TM/2000-05.

[3] J. Lagoda *et al.*, "Electron Drift Velocity measurements from the T600 half-module test", ICARUS-TM/2002-17.

[4] G. Battistoni *et al.*, "Preliminary analysis of cosmic ray induced interactions with π^0 and η^0 production", ICARUS-TM/2004-14.

[5] S. Amoruso *et al.*, "Analysis of the liquid Argon purity in the ICARUS T600 TPC", Nucl. Inst. Meth. A 516 (2004) 68.

[6] A. Ankowski *et al.*, "Energy reconstruction of electromagnetic showers from pi0 decays with the ICARUS T600 Liquid Argon TPC", Acta Phys. Polon. B 41 (2010) 103.

[7] R. Sulej *et al.*, "Search for CC tau neutrino interactions in CNGS beam using neural network", ICARUS-TM/20004-12.

[8] J. Lagoda *et al.*, "Polarization effects in tau production by neutrinos", Acta Phys. Polon. B 38 (2007) 2083.

[9] C. Anderson *et al.*, "The ArgoNeuT Detector in the NuMI Low-Energy beam line at Fermilab", JINST 7 (2012) 10019.

[10] LAGUNA-LBNO Deliverables for European Commission: S. K. Agarwalla *et al.*, "Optimised sensitivity to leptonic CP violation from spectral information: the LBNO case at 2300 km baseline". S. K. Agarwalla *et al.*, "The LBNO long baseline oscillation sensitivities with two conventional neutrino beams at different baselines".

[11] S. K. Agarwalla *et al.*, "The mass-hierarchy and CP-violation discovery reach of the LBNO long-baseline neutrino experiment", JHEP 1405 (2014) 094.

[12] K. Abe *et al.*, "The T2K Experiment", Nucl. Instrum. Meth. A 659 (2011) 106.

[13] S. Aoki *et al.*, "The T2K Side Muon Range Detector", Nucl. Instrum. Meth. A 698 (2013) 135.

[14] A. Vacheret *et al.*, "Characterization and Simulation of the Response of Multi Pixel Photon Counters to Low Light Levels", Nucl. Instrum. Meth. A656 (2011) 1, 69.

[15] A. Kiliński, „Badanie efektywności liczników w bliskim detektorze eksperymentu T2K przy użyciu mionów atmosferycznych", praca magisterska, 2011.

[16] K. Kowalik, J. Lagoda, W. Oryszczak, P. Przewlocki, "Off-bunch background study", T2K-TN-024 (2010).

[17] K. Kowalik, J. Lagoda, "The simulation of beam neutrinos interactions outside the ND280 detector", T2K-TN-077 (2011, 2012, 2013).

[18] J. Lagoda, "Estimation of the cosmic muons background", T2K-TN-112 (2012, 2013, 2014).

[19] K. Abe *et al.*, "Observation of Electron Neutrino Appearance in a Muon Neutrino Beam", Phys. Rev. Lett. 112 (2014) 061802.

[20] S. Berkman *et al.*, "fiTQun: A New Reconstruction Algorithm for Super-K", T2K-TN-146 (2013).

[21] S. Berkman *et al.*, "Data/Monte Carlo Simulation Comparisons with fiTQun ", T2K-TN-153 (2013).

[22] K. Abe *et al.*, "Neutrino oscillation physics potential of the T2K experiment", PTEP 2015 (2015) 043C01.

[23] N. Abgrall *et al.*, "Measurements of $\pi^{\pm}$, $K^{\pm}$, K^0_S, Λ and proton production in proton–carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS", Eur. Phys. J. C76 (2016) 2, 84.

[24] W. Oryszczak, W. Warzycha, "FGD systematics: PID and IsoRecon hybrid efficiency", T2K-TN-223 (2015).

[25] K. Abe *et al.*, "Precise Measurement of the Neutrino Mixing Parameter θ_{23} from Muon Neutrino Disappearance in an Off-Axis Beam", Phys. Rev. Lett. 112 (2014) 181801.

[26] K. Abe *et al.*, "Measurements of neutrino oscillation in appearance and disappearance channels by the T2K experiment with 6.6×10^{20} protons on target", Phys. Rev. D 91 (2015) 072010.

[27] P. Bartet *et al.*, "ν_μ CC event selections in the ND280 tracker using Run 2+3+4", T2K-TN-212 (2015).

[28] V. Berardi *et al.*, "CC $\bar{\nu}_\mu$ event selection in the ND280 tracker using Run 5c anti-neutrino beam data", T2K-TN-224 (2015). Uzupełnienie: "CC $\bar{\nu}_\mu$ event selection in the ND280 tracker using Run 5c and Run 6 anti-neutrino beam data", T2K-TN-246 (2015).

[29] V. Berardi *et al.*, "ND280 Tracker analysis of ν_μ Contamination In AntiNu Beam in Run5c data", T2K-TN-227 (2015). Uzupełnienie: "CC ν_μ background event selection in the ND280 tracker using Run 5c+Run 6 anti-neutrino beam data", T2K-TN-248 (2015).

[30] K. Abe *et al.*, "Measurement of muon anti-neutrino oscillations with an accelerator-produced off-axis beam", arXiv:1512.02495 [hep-ex].

[31] G. de Rosa *et al.*, "CC antineutrino multipion studies", T2K-TN-273 (2016).

[32] J. Lagoda, "Probing high energy, kaon-originated neutrinos with sand muons", T2K-TN-289 (2016).

[33] J. Lagoda, "Sand muon studies in ND280", T2K-TN-271 (2015).

[34] N. Abgrall *et al.*, "NA61/SHINE facility at the CERN SPS: beams and detector system", JINST 9 (2014) P06005.

[35] P. Lasorak, N. Prowse, "TITUS: An Intermediate Distance Detector for the Hyper-Kamiokande Neutrino Beam", arXiv: 1504.08272 [physics.ins-det].

[36] K. Abe *et al.*, "Letter of Intent: The Hyper-Kamiokande Experiment — Detector Design and Physics Potential", arXiv: 1109.3262 [hep-ex].

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