Appendix No. 2b to the "Wniosek o wszczęcie postępowania habilitacyjnego"
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Autoreferat

(summary of research accomplishments)

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1 Personal data

Name: Michał Szleper

2 Education

- 1996: Doctor of physical science, A. Sołtan Institute for Nuclear Studies
  Title of Ph.D. thesis: *Precision measurement of the structure function ratio* F_2^{Sn}/F_2^{C}
  Thesis advisor: Prof. Jan Nassalski
  Reviewers: Prof. Andrzej Eskreys, Prof. Jan Królikowski

- 1990: M.Sc. in physics, specialty: physics of elementary particles, Faculty of Physics, University of Warsaw
  Title of M.Sc. thesis: *Study of nuclear effects in deep inelastic muon scattering on* ^{6}Li, ^{12}C *and* ^{40}Ca
  Thesis advisor: Dr. Jacek Ciborowski

3 Information on employment

in reversed chronological order

- **2012 to date** - Adiunkt, National Center for Nuclear Research, Warsaw;
- **2001-2007** - Research Associate, Northwestern University, USA;
- **1996-2012** - Adiunkt, A. Sołtan Institute for Nuclear Studies, Warsaw;
- **1996-1997** - Postdoctoral Fellow, University of Edinburgh, UK;
- **1991-1996** - Physicist (Ph.D. student), A. Sołtan Institute for Nuclear Studies, Warsaw.

4 Curriculum vitae

4.1 Until my Ph.D.

My master thesis was related to the NA37 experiment at CERN, better known as the New Muon Collaboration (NMC). After my master's defense, in 1991, I was employed in the Institute for Nuclear Studies in Warsaw as a physicist (at that time there was officially no Ph.D. program in the INS) and joined the Warsaw NMC group with the objective of doing there my doctor degree. The subject of my research concerned measurements of the structure functions of nucleons bound in atomic nuclei via the process of deep inelastic muon scattering on nuclei. The topic was strictly connected to the so called EMC effect, first observed a few years before and being back then one of the main topics of interest in the particle physics community. It regarded the question why and how does the nucleon structure function F_2 measured on a nucleus differ from the one measured on a free nucleon. In my Ph.D. period the NA37 experiment did not collect data anymore, but rather final analyses of previously collected data were in full progress. I became acquainted with the apparatus itself practically during the runs of NA47, which was the NA37 successor (better known as the Spin Muon Collaboration, SMC), in which I also participated. The physics result of my NMC work was a precise measurement of the ratio F_2^{Sn}/F_2^C as a function of the Bjorken scaling variable x and of its Q^2 dependence (the square of the four-momentum transfer in the muon-nucleus interaction), as well as the demonstration that the observed dependence is precisely of the order expected by the evolution equations of Quantum Chromo-Dynamics (QCD). To this date it is the only such measurement of sufficient precision to hint at the existence of any such dependence. My Ph.D. was the very last Ph.D. completed within the NMC, hence it was largely my responsibility to produce the final collaboration results and prepare the publication. I was also involved in the publication committee of another paper related to nuclear structure functions.

During my Ph.D. program I was invited as a guest, three times for one month long visits each, to the Max Planck Instutute at Heidelberg. Together with a strong local team of physicist involved in the NMC data analysis, I worked, among other things, on new data formats for the experiment to facilitate analysis involving very large (for their time) datasets. Results related to my Ph.D. were shown by myself twice in international conferences and twice in domestic seminars. I am a coauthor of 12 publications by the NMC collaboration and 12 publications by the SMC collaboration.

4.2 First period after my Ph.D.: activities related to the physics of CP violation in quarks and neutrinos

After completing my Ph.D. I acquired the position of Adiunkt at the Sołtan Institute for Nuclear Studies in Warsaw. Upon completion of the last NMC related activities, I changed my main physics interests towards widely understood electroweak physics. In the mid-1990's virtually nothing was known about CP violation, except the original observation of K_L decay into two pions of 1964, and measurements of the closely related charge asymmetry in K_L semileptonic decay channels. In 1996, together with a group of physicists from the INS, I joined the NA48 experiment at CERN whose main physics topic was "direct" CP violation (i.e., occuring via the decay amplitude between two states of well defined, opposite CP) in the neutral kaon system.

The period between November 1996 and November 1997 I spent as a Post-doctoral Fellow at the University of Edinburgh. About a half of that time I was based physically at CERN to work directly on the NA48 experiment which was then entering its first year of data taking. During this period I was responsible for the operation of the Muon Veto Monitoring system at NA48; I was the author of an essential part of the monitoring code which was used in later years in a practically unchanged form [1]. I was also involved in physics data analysis related to the primary goal of the experiment, which was precise measurement of the ratio ϵ'/ϵ, a number that describes direct CP violation in the neutral kaon system. My research included studies of systematic effects related to detector acceptance via measurements of K_S and K_L lifetimes. These activities were carried on after my return to Warsaw; their byproduct was a publication on precise K_S lifetime determination based on all the NA48 data (however, being already involved in other projects, I let other people finish the work).

A temporary episode in my NA48 related activities was also the search for light gluinos, the supposed supersymmetric partners of gluons, in the mass range of a few GeV. Such gluino would be sufficiently long-lived to create a bound state with a gluon, the so called R^0, before decaying. This possibility, based on a possible interpretation of LEP data, had been just before noticed by Farrar [1] and became the subject of considerable controversy. NA48 turned out to be the ideal experiment to provide empirical verification of this realization of Supersymmetry. I was one of two persons inside NA48 who acknowledged the potential role of the experiment in settling the dispute, carried required Monte Carlo simulations and a fast analysis of already existing data (internal rules inside NA48 required at least two independent analyses for a physics result be published). Our publication closed for many years the ongoing discussion about the "light gluino window", as was called the hitherto unexplored parameter space in Supersymmetry where the gluino could be very light. The paper on light gluinos was the first physics paper by NA48.

Between 2001-2002 I was the head of the grant awarded by the Polish Committee for Scientific Research (KBN), entitled *Eksperyment NA48 w CERN: opracowanie danych i analiza fizyczna*. The grant was the financial basis of the Warsaw physics group activities in NA48 in the period. These activities included: participation in Monte Carlo simulations for the measurement of ϵ'/ϵ, measurements of K_S and K_L lifetimes and studies of rare kaon decays, $K_{S,L} \to \pi^+\pi^-\gamma$ and $K_{S,L} \to \pi^+\pi^-e^+e^-$.

A second phase of my increased NA48 involvement corresponds to the period 2003-2005 and was related to the NA48/2 project that will be discussed further below. I have presented NA48 results (including NA48/2) several times in international conferences and institute seminars [2].

The end of 1990's in particle physics stood also for the first observation of neutrino oscillations by Super-Kamiokande. As of 1999, I was engaged in the process of setting up a strong neutrino group in Warsaw. I was one of the first physicists from Warsaw who became actively involved in various activities related to the ICANOE/Icarus project at Gran Sasso. Under my supervision carried were simulations for the design of an exter-

[1] See NA48 internal note "The Muon Veto Monitor", NA48-04/98, of my authorship.

[2] For more detailed information on my conference and seminar presentations since my Ph.D. see Appendix 4.

nal trigger for the Icarus detector. The trigger was designed to demonstrate the crucial detection capabilities of long muon tracks in a large detector based on the liquid argon technology [2]. My subsequent several short visits to Gran Sasso and Pavia, Italy, were concentrated on trigger testing and installation, as well as other work related to preparations of the first half of the T300 module. The trigger system we had fully authored served during test runs for Icarus in 2001 [3].

The entire period between January 2001 and May 2007 I spent in the United States where I worked as Research Associate at Northwestern University. Until 2005 my main research fields remained neutrino oscillation projects and NA48.

Soon after the first observation of neutrino oscillations a question arose whether CP violation is present also in the neutrino sector and whether it can help explain the puzzle of matter-antimatter asymmetry in the Universe. The first step in this direction would have to be the measurement of a non-zero θ_{13} angle in the neutrino mixing (MNS) matrix and that in turn would require observation of the subdominant oscillation mode $\nu_\mu \rightarrow \nu_e$. As member of the Northwestern neutrino group, I collaborated with physicists of the MINOS experiment, my personal task being preparation of a future measurement of ν_e appearance. I was the first person who started detailed systematic simulation studies focused on the recently proposed concept of placing the far neutrino detector at a non-zero angle with respect to the NuMI (Neutrino Main Injector at Fermilab) beam axis. The project was initially known as NuMI Off-Axis, eventually to become the currently operating NOvA experiment. The Off-Axis concept was a reference to the fact that the neutrino beam spectrum at a finite angle has several significant advantages over the on-axis spectrum. In short, an off-axis detector allowed for a much better ν_e appearance measurement without requiring redesign of the beamline. My most personal contribution to the subject was suggesting an original method for the reference spectrum evaluation, i.e., the spectrum in the far neutrino detector expected in the absence of neutrino oscillations. The method consisted in deriving, based uniquely on calculable kinematic bounds, the so called Near-to-Far Matrix via which one could directly obtain the expected neutrino energy spectrum in the far detector that corresponded on a statistical basis to each neutrino detected in the near detector, the latter assumed to be on-axis. The key issue was to prove that any uncertainties in the determination of the matrix itself, for instance those coming from hadron production spectra in the primary proton-target interaction, to a large extent cancel out during the transition from the near to the far detector. Regardless of these uncertainties, as well as of the actual position of the far detector, the matrix technique allowed to predict the reference spectrum with a high accuracy. The original motivation of the Near-to-Far matrix was the Off-Axis project, but it soon turned out that this technique can significantly reduce the systematic uncertainties also for an on-axis far detector. The method, in a somewhat upgraded version, is presently known as the "Matrix Method" and is still used in the MINOS experiment. Two early papers whose I am one of two authors [3], and two further ones whose I am one of several authors [4], provided the conceptual foundations for the NuMI Off-Axis project in its initial shape and although they were never officially published (they remained as Fermilab reports or NuMI internal notes and arXiv preprints) to this date they are highly quoted.

The Near-to-Far Matrix technique and related studies for NuMI Off-Axis were pre-

[3] See also Icarus internal note "An external trigger system for the ICARUS T600 test", ICARUS-TM/2000-05.

sented by myself in a number of conferences and workshops in 2001-2002. These were mostly invited talks. In 2002 I participated also in the Aspen (Colorado, US) study whose main topics were setting up a roadmap for neutrino physics in the United States and the choice of appropriate sites for future neutrino detectors [5].

After 2002 my activity in neutrino physics waned due to Northwestern University withdrawal from neutrino projects.

In 2003, a new NA48/2 project started at CERN whose main aim was the search for direct CP violation in the charged kaon system via precise measurement of the asymmetry in the decays $K^{\pm} \to 3\pi$. I participated in the project during the next couple of years. My most direct contribution to the primary physics result of NA48/2 involved a study of forgotten systematic effects related to the presence of parasitic, rudimentary magnetic fields in the decay volume of the experiment. Correct consideration of those fields in the reconstruction of the $K^{\pm}$ decay kinematics had a significant impact in the evaluation of final results, mostly in the kaon decays to three charged pions. The charged decay mode possessed the largest statistical power and ultimately provided the most accurate test of the Standard Model done at NA48/2.

By all practical means I was an auxiliary supervisor of a group of undergraduate and graduate students who worked in NA48/2 on various specific topics related to $K^{\pm}$ semileptonic decays. One of the main motivations of this research was the existing controversy concerning the quark mixing (CKM) matrix element V_{us} whose best world value, according to the PDG'2002, deviated from the Standard Model, albeit not in a statistically conclusive way [6]. A preliminary express analysis of the decays $K^{\pm} \to \pi^0 e^{\pm} \nu$ ($K^{\pm}_{e3}$) from NA48/2 data was done in a large extent by myself. It produced a new result for V_{us}, with a precision better than 1%, and fully consistent with the Standard Model. The result was shown still in the same year in international conferences as "NA48/2 preliminary" and practically settled the V_{us} controversy. In the next step, a full, final analysis, extended by addition of the $K^{\pm} \to \pi^0 \mu^{\pm} \nu$ decay channel, was carried in terms of a Ph.D. thesis completed at Northwestern University under my auxiliary supervision [4].

To this date I am a coauthor of all the publications by NA48/2.

4.3 Activities related to the mechanism of electroweak symmetry breaking

4.3.1 The linear electron-positron collider

During my period based at Northwestern I got in touch with a physics group involved in various studies related to the project of building a future linear electron-positron collider (LC, presently ILC and CLIC). The group was mainly interested in the photon-photon collider option that could be built based on the e^+e^- beams and the physics related. The Linear Collider was formally never my main research topic, however I praticipated in many discussions and was often asked to provide scientific feedback in a number of issues. This feedback included self-made calculations, simulation work and student supervision.

[4]This fact has not been formalized in any existing documentation, but in making the above claim I have the support of the persons in question. See also "Prace doktorskie, których byłem pomocniczym opiekunem" in Appendix 4.

With varying intensity, my collaboration with the $\gamma\gamma$ group lasted for several years, in certain periods taking even the better part of my time.

One of my first original results was an order of magnitude estimate of the effects of deep inelastic scattering (obvious reference to my Ph.D.) of electrons off nuclei in the crystal lattice in a considered alternative concept of photon beam production. According to this idea the photon beams would be obtained by placing a crystal in the e^+e^- beamlines. The physics mechanism of producing circularly polarized high energy photons in a crystal lattice was first proposed on theoretical grounds by Cabibbo [7], then proved empirically by the NA59 experiment at CERN (R&D) [8]. Nevertheless, the result of my calculation was decidedly negative and forced to abandon this concept as an option for the LC.

Later on I participated in studies of the physics potential of the $\gamma\gamma$ option as a Higgs factory, with special consideration given to non-standard physics scenarios, difficult to detect at the LHC. These studies were carried within the LHC/LC Study Group. I was the first author of a work concerning the capabilities of Higgs boson detection in the NMSSM (Next-to-Minimal Supersymmetry) scenario, where a light Higgs scalar would decay into two light pseudoscalars ($h \to aa$), in a $\gamma\gamma$ collider built on a CLIC-type machine [9]. Considered were different options of the obtained $\gamma\gamma$ spectrum. The conclusion of the study was that the proposed analysis of a final state consisting of four b quarks, or two b quarks and two τ leptons, could provide a significant motivation for having a $\gamma\gamma$ collider, assuming a low energy CLIC-type machine would be built still before ILC construction. Supposedly, this kind of analysis should become one of the main points of physicists' interest, should the LHC fail to observe the Higgs boson in at least one of its standard mainstream decay channels. Since real facts turned to be different in the end, the work in its original shape has now lost its actuality. However, some of my contributions to the applied simulation tools and analysis techniques can still be relevant.

I participated in discussions carried within the American physics community on possible sites to host a linear collider. As part of the ongoing discussion, measurements and a full Fourier analysis of seismic activity in the Fermilab site as a function of depth below ground level were done by myself and under my scientific supervision. In making these measurements we took advantage of the 3-dimensional geometry of the NuMI tunnel just before installation of the entire infrastructure for the MINOS experiment. A report is available [10].

My results were shown several times on LC collaboration meetings and once on the APS (American Physical Society) conference. I am listed as a coathor of four volumes of the *ILC Reference Design Report* that appeared in 2007 [11].

4.3.2 The CMS experiment at the LHC

As of 2005, my main research project is the CMS experiment at the LHC. As a member of Northwestern University I joined the widely understood efforts related to preparations of the CMS Hadronic Calorimeter (HCAL) for the first LHC collisions. In this entire period my previous physics activities were practically suspended because of the large amount of work related to the forthcoming LHC startup.

In the period of CMS detector commissioning I participated in construction work of HCAL readout modules and in preliminary calibration of the calorimeter using a radioactive source technique during its assembly in the SX5 hall at CERN. I helped develop the code that was used for quality control (QC) of the individual HCAL readout modules just before and after their installation on the detector. I was one of 7 authors of one of the first CMS HCAL technical notes which reported the first successful attempts to detect cosmic muons using solely signals in the calorimeter [12].

In 2006 I became responsible for providing an initial HCAL calibration before the appearance of the first LHC data. The ultimate goal of my work was to ensure reasonable reconstruction of energy deposits in the calorimeter at the moment when first collision data were supposed to come, before these data would enable a more accurate calibration. Specific tasks I worked on, together with a few people strong group of experts, included:

- working out methods of individual calibration of the calorimeter cells and their implementation in the newly created CMS software framework (CMSSW),
- definition of data formats for calorimeter calibration during the run, and of unified calibration constants per readout channel, to be used in data reconstruction as well as for physics simulations,
- writing code for the monitoring of HCAL pedestals and their stability during data taking, as well as more detailed studies of calorimeter operation to be carried off-line,
- writing code for precise time alignment of HCAL signals using a built-in laser beam and LED system.

During Test Beam runs involving parts of the calorimeter (2006) and during global tests known as the MTCC (Magnet Test and Cosmic Challenge, in practice the first serious integration tests of all the subsystems of the CMS detector) I was responsible for setting up and continuous operation of the calibration software and for communications with the database. I supervised the calculation of the relevant calibration constants, continuous monitoring of pedestals and updating their respective values in the database. My responsibility was also to keep an up-to-date HCAL electronics map (frequently changing in that period) in a format ready to be used for ongoing data analyses by other groups.

I am the author of various parts of the HCAL code in CMSSW in what concerns calibration and energy reconstruction. This code, albeit with many later modifications, is still in use in CMS. From 2006 until my departure from the US (April 2007) I was the contact person between the HCAL detector group and the Jet-MET group (reconstruction of jets and missing energy) inside the CMS collaboration. I also tried to be, however within very modest time frames, the contact person with the newly established Particle Flow group (a technique of event reconstruction based on simultaneous usage of information from all CMS subdetectors in order to identify particles).

A significant part of my HCAL related activities in CMS were teaching and advisory activities, most of all in what concerns operation and usage of the HCAL code in CMSSW, especially those parts of it that I had authored. In the summer of 2006 I organized a tutorial session at CERN [5].

My activities for CMS HCAL are well documented in numerous presentations in internal HCAL meetings between 2005-2006.

[5] See `http://diablo.phys.northwestern.edu/~michals/cmssw_tutorial.html`.

In 2007 I returned to Poland and joined the Warsaw CMS group. I took over a part of the group responsibilities concerning the setup and operation of a muon trigger based on the Resistive Plate Chamber (RPC) system. My contribution included the definition of basic objects in CMSSW for the description of the RPC trigger configuration, their unification within a larger frame of the global CMS trigger configuration and communications with the database (the objects in question are: the current electronic cabling map, the full set of muon patterns that are used to issue triggers, as well as other parameters that define the full operation mode of the RPC trigger). In the relevant period when the CMS database concepts were being defined, I was the contact person between the CMS database group and the RPC trigger group. I also contributed to the development of the RPC trigger monitoring system. The latter involved important improvements to the existing trigger emulator code which ultimately allowed to have an exact prediction of the output of a correctly operating trigger hardware based on simultaneous processing of RPC chamber data by the trigger emulator.

During my many visits to CERN between 2008-2012, I was an on-call expert responsible for the RPC trigger operation, first in CMS test runs and subsequently during physics data taking.

On two occasions I participated in editorial committees on behalf of the RPC group and provided relevant parts of text for CMS publications concerning trigger operation.

Inside the Warsaw CMS group, throughout a period of two years I organized quasi-regular bi-weekly physics meetings with the aim of discussing current progress in physics data analyses done by members of the group, as well as other physics news from CMS and related topics.

In what regards physics my main topic of interest for the last few years has been study of the vector boson scattering process, VV, where $V = W^{\pm}, Z$, at high energies. It is an important test of the mechanism of electroweak symmetry breaking in the Standard Model. Historically, the interest in VV interaction was closely related to the question of the very existence - or non-existence - of the Higgs boson. Afterwards it became the key process for the empirical verification of whether the Higgs boson indeed fulfills its task assigned to it by the Standard Model. According to theory, the same Higgs boson should also ensure unitarity in the interaction between vector bosons of longitudinal polarization ($V_L V_L$). The entire energy dependence of the $V_L V_L$ scattering cross section is fully defined by merely a few numbers that are completely determined within the Standard Model framework. Its experimental verification will provide an ultimate closure test of the Standard Model or the theory that will replace it.

I was the main driving force behind establishing a successful collaboration with a group of internationally renowned theoretical physicists from the University of Warsaw and carrying detailed simulation work to study the WW scattering process at the LHC. The outcome of this collaboration was a phenomenological paper [13] where we suggested a novel analysis strategy for the LHC at 14 TeV, based on originally derived selection criteria. The selection criteria were specifically focused on maximizing the sensitivity to possible deviations from the Standard Model, while keeping all the realistic analysis features of a real CMS-like experiment. A novel feature of our approach resided in showing that polarizations of the vector bosons can be effectively separated based on transverse momentum spectra of the so called "tagging jets", i.e., those associated to the vector boson fusion (VBF) process. Therefore, it is possible to improve sensitivity to physics related to the electroweak symmetry breaking mechanism (which affects only $V_L V_L$ pairs) and separate possible effects of other physics.

Our work has already helped increase attention to the same-sign scattering process, $W^\pm W^\pm$, whose many advantages, both theoretical and experimental, we recapitulated and further elaborated on in our paper. CMS has already produced a first result on the $W^\pm W^\pm$ process based on data collected at 8 TeV, the paper is currently awaiting final publication [14]. A similar analysis has also been done by the ATLAS collaboration [15]. Although these works are presented as Standard Model measurements and are hardly conclusive in terms of possible contributions from physics beyond the Standard Model, they set the path towards future measurements at higher energies. An update of the results of our phenomenological paper, in the light of new data coming from LHC experiments, was the subject of a bachelor thesis at the University of Warsaw, written under my supervision (2013).

Plans for future analyses at the LHC are currently discussed in loose collaboration with the Technische Universität in Dresden that participates in the ATLAS experiment. Physicists from Dresden were directly involved in the $W^\pm W^\pm$ analysis at 8 TeV produced by ATLAS. Our cooperation concerns mainly conceptual aspects, as well as technical problems that are common to both LHC experiments, in particular the problem of many proton-proton interactions occurring in a single bunch crossing (pile-up) and the resulting limitation on our ability to select a clean $V_L V_L$ sample.

The process of VV scattering is also mentioned among the main physics motivations for the construction of future circular colliders (FCC) operating at much higher energies than available at the LHC. The FCC offers significantly better perspectives for the physics of VV scattering and provides a logical continuation of the work done at the LHC. As one of six physicists from Poland I participated in the FCC Kick-Off Meeting held in February 2014 at the University of Geneva [16]. Together with a group of physicists from the Institute for Theoretical Physics at the University of Warsaw we have established a preliminary collaboration with the FCC-hh (hadron-hadron option) project. The aim is to carry first dedicated simulations of proton-proton interactions at a center of mass energy of 100 TeV, for preliminary studies of W^+W^+ scattering effects. Current key topics of my work are:

- how does the kinematic signature of WW scattering (longitudinal pairs in particular) changes at 100 TeV compared to 14 TeV,
- what is the sensitivity of W^+W^+ scattering at 100 TeV to the Higgs coupling to WW, to triple couplings WWZ, $WW\gamma$ and the quartic coupling $WWWW$ within present experimental bounds,
- what is the kinematic separation of longitudinally polarized WW pairs versus the remaining WW pairs and how this separation translates into our ability to separate effects coming from different physics sources.

A working group to address the abovementioned issues is currently under construction. A rough overview of topics, along with some first fragmentary simulation results were already presented by myself in an FCC-hh working group meeting.

The process of VV scattering is also the subject of a comprehensive monograph whose I am the only author and I herewith enclose as my scientific achievement.

5 Presentation of the scientific achievement

As my scientific achievement I present the monograph entitled:

"The Higgs boson and the physics of WW scattering before and after Higgs discovery",

issued by the National Center for Nuclear Research, **ISBN 978-83-934358-7-6**, and whose I am the only author. The work has been also placed on the Cornell University library archieve of preprints under the number arXiv:1412.8367.

The monograph herewith presented has been conceived as a possibly wide overview of the subject of vector boson scattering, both from the theory as well as from the experimental side, in the dawn of Run 2 of the LHC. Recalled in it are the very physical basics, the historical relation between WW scattering and the mechanism of electroweak symmetry breaking and the Higgs boson in particular. A review is presented of existing phenomenological works and the most important experimental results concerning the Higgs boson and electroweak physics of most relevance to the main topic. Finally, sketched are the future perspectives and emphasized the importance of the process in searches for new physics after Higgs discovery - both at the LHC and beyond.

The first chapter of the monograph is a short introduction that explains the concept of spontaneous symmetry breaking and emphasizes its special importance in modern particle physics, including its relevance to explain the origin of mass in the Universe, especially after Higgs boson discovery. The main goal of the LHC is to explain the mechanism of electroweak symmetry breaking in nature. Higgs boson discovery gives us an important hint, but does not yet give an answer to all our questions. Those will still be the research topics for many forthcoming years, addressed among other ways via measurements of VV scattering. Chapter 1 contains also a brief abstract of the contents of next chapters.

Chapter 2, "The Higgs boson in the Standard Model", explains the relation between WW scattering and the Higgs boson from a theoretical point of view. It presents a semi-historical sketch of the beginnings of the modern theory of electroweak interactions, from the origins of the W and Z weak bosons concept to the Higgs boson concept as the key component of the Standard Model of elementary particles. It emphasizes the twofold role of the Higgs boson in the Standard Model, which is reflected in two in principle independent ways to introduce the Higgs to the theory. It turns out that the massiveness of the weak bosons W and Z is a source of two serious problems in the theory, and that both can be solved by inclusion of a Higgs boson. In the most known, paperbook derivation of the Higgs boson concept, it appears in the theory as a byproduct of spontaneous $\mathrm{SU}(2) \times \mathrm{U}(1)$ gauge symmetry breaking, the result of a quantum-mechanical choice of a single vacuum state, if only we assume *ad-hoc* existence of some self-interacting, complex scalar field described by the so called Higgs potential. Non-zero masses of gauge bosons can be generated in the process via the Higgs mechanism (more adequately called the

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism) that essentially means interaction of the initially massless vector bosons with massless scalar fields. In this way, the Standard Model Lagrangian exhibits required gauge invariance, but the lowest energy solution (massive W and Z bosons in particular) does not.

The second problem related to non-zero gauge boson masses is the possibility of their longitudinal polarization which leads to violation of unitarity in VV scattering processes at sufficiently high energies. Since the connection between W and Z longitudinal polarization and the question of unitarity in the Standard Model is the central topic of the entire work, the objective of Chapter 2 was to present a detailed explanation of the problem from first principles, however avoiding being a regular lecture on theoretical physics. It turns out that the same Higgs boson can cause removal of all the occurring divergences and restoration of unitarity in the theory, provided that its couplings to the W and Z bosons are exactly as predicted in the Standard Model (also that couplings between gauge bosons themselves are exactly as in the Standard Model). The full energy dependence of VV scattering processes is defined by Higgs couplings to gauge bosons and by triple and quartic gauge boson couplings. Non-Standard Model scenarios will usually result in a different shape of this spectrum than in the Standard Model.

Despite experimental observation of the Higgs boson, we still do not know whether it really fulfills the second task ascribed to it in the Standard Model. If the Higgs does not fully ensure $V_L V_L \to V_L V_L$ amplitude unitarization, there may still be partially strong VV scattering and dynamic heavy resonances, in a manner foreseen by Higgsless scenarios. Only direct observation of VV scattering at high energy can definitely answer this question.

Chapter 2 contains also a conceptual introduction to the Electroweak Chiral Lagrangian (EWChL) formalism, both as a historical alternative to the Standard Model solution, but most of all as an effective way of description of unknown new physics, derived from the general principles of Quantum Field Theory. While before Higgs discovery the EWChL applications were focused on phenomenology related to alternative mechanisms of electroweak symmetry breaking (strictly speaking, W and Z mass generation via the Higgs mechanism requires necessarily existence of only three scalar fields and in the most general case it does not imply Higgs boson existence, but unitarity in VV interactions has to be then ensured in the theory in other ways), the same formalism is still useful today and with some modifications can be applied in phenomenological studies of physics beyond the Standard Model. The question will still be discussed in the next chapter.

The third chapter of the monograph, "Standard Model experimental status and prospects for BSM", contains an up-to-date review of experimental results concerning the Higgs boson and electroweak physics, with emphasis on recent results of LHC experiments from 2011-2012 [6]. These results are of paramount importance when it comes to future perspectives for VV scattering measurements at the LHC or in envisaged future colliders.

Vector Boson Fusion (VBF) is one of the known mechanisms of Higgs boson production at the LHC. If followed by Higgs decay into a W^+W^- pair, it is physically identical with W^+W^- scattering at an energy equivalent to the Higgs mass. Therefore, the basic topological signature of WW scattering in the CMS or ATLAS detectors is well known

[6] A comprehensive list of references and additional literature is given in the work itself, given their large number the references will not be repeated in this summary.

experimentally. Standard selection criteria make however no distinction between different helicity combinations of the WW pair.

The Higgs mass has been precisely determined from a combination of data from two leading decay modes: $H \to ZZ^* \to l^+l^-l^+l^-$ and $H \to \gamma\gamma$. Its up-to-date values are: $M_H = 125.36 \pm 0.37(stat) \pm 0.18(syst)$ GeV (ATLAS) and $M_H = 125.03 \, ^{+\,0.26}_{-\,0.27}(stat) \, ^{+\,0.13}_{-\,0.15}$ $(syst)$ GeV (CMS). Comparison of masses determined by ATLAS and CMS from the two channels separately force to conclude that within the present resolution limits there is indeed a single resonance. A statistically significant Higgs signal has also been observed in the decay channel $H \to W^+W^- \to l^+l^-\nu\nu$. Independent confirmation of Higgs existence was obtained as well in the channel $H \to \tau^+\tau^-$, which to this date provides the most direct evidence that the Higgs couples to fermions, as expected in the Standard Model. Strong indirect evidence that the Higgs couples to fermions is also obtained from the fact that the total Higgs production rate, dominated mainly by gluon-gluon fusion with top quark loops in the Standard Model, agrees with expectations.

Crucial to the identification of the observed resonance with the Higgs boson is measurement of its spin and parity - the Standard Model Higgs is a pure scalar, $J^P = 0^+$. Higgs spin and parity is determined from comparison of the measured angular distributions of its decay products with predictions derived under different working hypotheses. In practice, each alternative hypothesis is tested against the reference $J^P = 0^+$ hypothesis. Simulated maximum likelihood distributions are directly compared with the measured experimental result, which allows rejection of one of the two hypotheses at a confidence level that depends on the separation of the two simulated distributions. The most significant results are obtained from the $H \to ZZ^* \to l^+l^-l^+l^-$ channel, where compared are distributions of five different angles that fully characterize this decay. Full combination of decays $H \to ZZ^* \to l^+l^-l^+l^-$, $H \to \gamma\gamma$ and $H \to W^+W^- \to l^+l^-\nu\nu$ suffices presently to discard all non-standard hypotheses with a confidence level (CL) of 99% or higher. However, one cannot exclude a mixed parity state, e.g. $0^+ + 0^-$, provided the non-standard contribution accounts for not more than about 40% of the total cross section (95% CL limit).

Mostly important from the VV scattering point of view are measurements of Higgs couplings to the gauge bosons. Experiment can determine directly the so called signal strength μ for a given decay channel, e.g., WW or ZZ. Results are so far consistent with SM predictions within an error margin of 20-30%. For instance CMS obtained $\mu_{WW} = 0.83 \, ^{+\,0.22}_{-\,0.20}$ and $\mu_{ZZ} = 1.00 \, ^{+\,0.32}_{-\,0.26}$, expressed in units where the Standard Model is defined as unity in each decay channel separately. More sophisticated analyses categorize the data according to their full production + decay path, where each production mechanism is tagged via requirements of certain topological and kinematic features that are instrumental in selecting the requested mechanism. For practical reasons, however, one cannot in this way completely determine all the couplings independently of each other. Moreover, the procedure is not completely model independent (as explained in detail in the monograph). From fits in which only a global modification of all bosonic couplings and a global modification of all fermionic couplings were allowed (hence two free parameters), one gets agreement with the Standard Model within ~10% for bosons and ~20% for fermions.

Both ATLAS and CMS carried a large number of dedicated searches for non-Standard Model Higgs bosons. Additional SM-like Higgses have been excluded up to 710-850 GeV, depending on the decay channel. Higgs searches within the framework of the Minimal Supersymmetric extension of the Standard Model (MSSM) gave negative results and have been translated into stringent limits in the MSSM parameter space of the Higgs sector, M_A vs. $tan\beta$. However, the hypothesis that the only discovered Higgs boson is in fact the lighter of the two neutral scalars predicted by the MSSM cannot be completely ruled out. Searches for other non-standard Higgs signatures, e.g. the ones predicted in other supersymmetric scenarios (NMMSM) or more exotic models, did not lead to observation and were translated into respective limits on the production cross section or model parameters.

Equally important from the VV scattering point of view are electroweak physics results (section 3.2). Experiments on the LHC carried precision measurements of cross sections for inclusive diboson production, W^+W^-, WZ, ZZ, $W\gamma$ and $Z\gamma$, at 7 and 8 TeV. Of special importance for us are those measurements that translate into coupling strengths between W and Z bosons and the photon. Deviations from the Standard Model, expressed in terms of anomalous triple couplings, WWZ and $WW\gamma$ in particular, were searched for based on the measured kinematics of gauge bosons in the final state. New LHC measurements have fully confirmed earlier LEP and TeVatron results and indicated agreement with the Standard Model. A new combination of world data provides the most updated limits on anomalous triple couplings. The latter are currently often expressed in the language of anomalous coefficients, e.g., c_W, c_{WWW} and c_B, that scale higher (than 4) dimension operators in an effective extended Lagrangian within the framework of Quantum Field Theory. More detailed discussion of individual dimension-6 and dimension-8 operators that can be probed in VV scattering processes, their formal definitions and connections with the proper couplings, as well as VV helicities (which is an original point of view developed in this work), is presented in subsection 3.4.2. Expressed in this language current experimental 95% CL limits on dimension-6 operators affecting triple gauge couplings are at the level of $\pm$1-10/TeV^2. Section 3.4 presents examples of full energy dependences of the W^+W^+ scattering cross section, differentiating between helicity combinations W_LW_L and W_TW_X, calculated within the Standard Model and with the inclusion of anomalous Higgs couplings and anomalous triple and quartic gauge couplings. These are original calculations produced by myself for the sake of the present monograph.

Quartic couplings, in particular $WWWW$, can be determined via measurements of VV scattering or triboson production, but data taken at 7 and 8 TeV are of not enough statistical power to hold a truly conclusive analysis (discussion on the first measurements of $W^\pm W^\pm$ scattering carried by ATLAS and CMS will be given later on). Currently quartic couplings are largely unmeasured experimentally.

The remainder of chapter 3 presents a sketch of the physics landscape that emerges from the present experimental input coming from different parts of particle physics and astrophysics in what regards possible hints of physics beyond the Standard Model. It discusses a particular class of theoretical models that have been proposed as a possible Standard Model extension, known as the Strongly Interacting Light Higgs (SILH) models. In these models the Higgs is a composite object, belonging to a whole new, unknown sector, and - what's important - it does not ensure complete $V_LV_L \rightarrow V_LV_L$ amplitude unitarization. Such theories provide important and fully realistic motivation to study VV scattering. Predicted within are Higgs to gauge couplings and couplings between gauge bosons that deviate from the Standard Model. However, existence - or not - of partially strong VV scattering can be only proved via direct observation.

Chapter 4 of the monograph, "VV scattering at the LHC", presents a detailed analysis of the VV scattering process as seen at the LHC from the phenomenological point of view. At the LHC, VV scattering is identified via observation of the $jjVV$ final state, i.e., two gauge bosons (more exactly: its decay products) and two jets, called "tagging jets", oriented strongly forward/backward. However, the same signature can also be produced by events where no VV interaction has taken place. Their consideration is necessary not only for the correct assessment of background levels (this is the so called irreducible background, i.e., composed of the same physical particles in the final state), but - due to computational reasons - for the correct assessment of the signal itself. In section 4.1 different approaches to formal signal definition are presented and compared: those usually applied in data analysis in experiments like CMS and those that are useful in calculations and simulation-based studies, especially in those involving physics beyond the Standard Model. Because no set of selection criteria based on event kinematics guarantees selection of a pure event sample in which the scattering process indeed took place, and because scattering of longitudinally polarized pairs in the Standard Model is but a small fraction of the total VV production, it is most convenient for the sake of calculations to define the signal as the enhancement of V_LV_L pair production relative to Standard Model predictions. Signal evaluation requires thus two computations: one carried within the Standard Model (which at the same time stands for the total irreducible background) and one in a non-SM scenario. This definition can also be extended for the scenarios that modify transverse polarizations, too.

Presented in section 4.2 is a discussion on computational methods and approximations often applied in theoretical calculations, especially in older literature on the subject: the Effective W Approximation, the Goldstone boson Equivalence Theorem and the W on-shell approximation. The latter actually plays an important role in further considerations.

Sections 4.3, 4.4 and 4.5 contain a discussion of the entire VV scattering process, such as observed in the CMS detector, decomposed into three distinct steps: emission of gauge bosons off quarks, the proper interaction between gauge bosons and gauge boson decays with the resulting possible final states and experimental signatures. Purely leptonic gauge boson decays ($W \to l\nu, Z \to l^+l^-$, where l is either a muon or an electron) are chosen as the cleanest experimentally for a more detailed analysis. An essential question for the presented analysis concept is whether in the VV scattering process different gauge boson helicities can be reasonably separated from each other. In this work it is claimed that it makes the most physical, as well as practical, sense for the process of same-sign W boson scattering, i.e., $W^\pm W^\pm \to W^\pm W^\pm$. The following facts are shown as concerning $W^\pm W^\pm$ scattering at an energy much larger than the Higgs mass:

1. that the W bosons to a good approximation behave like on-shell, therefore have well defined helicities (section 4.2),

2. that processes $W_T^\pm W_X^\pm \to W_T^\pm W_X^\pm$ and $W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm$ in the Standard Model dominate by 2-3 orders of magnitude over $W_T^\pm W_X^\pm \to W_L^\pm W_L^\pm$ and $W_L^\pm W_L^\pm \to W_T^\pm W_X^\pm$ - also no physics beyond the Standard Model, described by means of Effective Field Theory, can generate a divergent increase of the amplitudes for $W_T^\pm W_X^\pm \to W_L^\pm W_L^\pm$ and $W_L^\pm W_L^\pm \to W_T^\pm W_X^\pm$,

3. that emissions of W_L and W_T off a quark line differ in angular distributions, this reflects in different transverse momentum spectra of the quark after the act of emission (section 4.3),

4. that the abovementioned differences in angular distributions should be mirrored at the level of transverse momenta of reconstructed tagging jets once appropriate basic toplogical selection criteria for VBF-like events are applied (section 4.6),

5. that if in addtion W_LW_L and W_TW_X pairs tend to populate different regions of invariant mass (e.g., because only W_LW_L get enhanced at high mass, as is the case of scaled Higgs to gauge couplings), then an effective variable that discriminates signal from background becomes the double ratio of transverse momenta, denoted by $R_{p_T} = p_T^{l_1} p_T^{l_2} / (p_T^{j_1} p_T^{j_2})$.

It is especially worth emphasizing that W_LW_L pairs correspond to systematically lower transverse momenta of the tagging jets than W_TW_X. From this it follows that applying high p_T thresholds on tagging jets, as is routinely practiced in order to protect from the beam pile-up (the effect of many proton-proton interactions occurring in a single bunch crossing), decreases sensitivity to physics related to the Higgs boson. It may become necessary to find additional algorithms of proper jet tagging in the presence pile-up jets, to cope with this problem. The entire chapter shows all the detailed kinematic spectra that are at the basis of the above observations, including a justification of the R_{p_T} variable; also shown is why all the above observations (except No. 1) apply *only* to the $W^{\pm}W^{\pm}$ process.

Section 4.7 contains a discussion of the main sources of reducible background, i.e., processes where the final state comprises other particles than the signal, but can mimick all the required signatures in a real particle detector. Potential sources of such backgrounds in the CMS experiment are: inclusive $t\bar{t}$ production (for $W^{\pm}W^{\pm}$ only if coupled with leptonic b quark decay or wrong lepton charge determination (sign-flips)), W+jets production with a jet misreconstructed as a lepton and QCD multijet events with two jets misreconstructed as leptons. Recalled here are the already known methods of background reduction for inclusive $t\bar{t}$ production processes. Also mentioned are various rough estimates of the relevant CMS and/or ATLAS detector capabilities such as b quark tagging efficiency in the endcap region, lepton charge determination efficiency as a function of transverse momentum, or the probability to reconstruct a jet or hadron as a lepton, that were based on various publicly available analyses and simulation studies, and that ultimately will define the amount of all the above backgrounds in future measurements at 13 TeV.

The last issue that is discussed in chapter 4 concerns pseudorapidity distributions of tagging jets for the signal and irreducible background. They show that the kinematic region of maximum sensitivity to Higgs couplings extends all the way down to pseudorapidities ± 5. This may have severe implications in the context of future upgrade plans concerning the hadronic calorimeter operation in the endcap (HE) and forward (HF) regions at CMS for the High Luminosity LHC program.

Most of Chapter 4 focuses on my own conceptual contribution to the subject of VV scattering, and results of my own simulation work. Part of these results were published in a previous paper [13], some have been also presented in internal meetings and seminars.

Chapter 5 of the presented monograph, "Simulation-based studies vs. experimental results", contains a review of the most important phenomenological works on the subject, from first pioneering calculation done for the sake of the planned Superconducting Super Collider, to calculations and simulation work carried in the context of the LHC at 14 TeV before Higgs discovery, to the most up-to-date papers written after Higgs discovery. In doing this review my main focus was on those elements of all the older works that fully keep their actuality in the changed physics context after 2012. Referring to the individual works and their conclusions in this short summary is inessential. However, the most important conclusion of Chapter 5 is that a lot on the selection criteria and analysis techniques proposed in the past to study alternative mechanisms of electroweak symmetry breaking have been these days undeservedly forgotten due to appearance of modern calculation tools and not least due to Higgs boson discovery. But this knowledge still can and should be taken full advantage of in future searches for physics beyond the Standard Model. Many older conclusions and predictions can be also reconfirmed using modern analysis tools. The above remains true even when the foremost motivation for studying WW scattering processes shifts from probing the Higgs boson to probing quartic gauge couplings. Revisiting the conclusions of many apparently forgotten earlier papers using modern tools is one of the primary goals of the present monograph.

Section 5.4 contains in addition a detailed discussion on the results of $W^{\pm}W^{\pm}$ scattering analyses carried recently by the ATLAS and CMS collaborations on 8 TeV data. The published results practically do not allow any relevant physics conclusions, either in what concerns the Higgs boson in WW scattering or (which is elucidated in the discussion) on quartic couplings. In contrast to all the phenomenological papers mentioned above, always done for beam energies larger than the currently available, the present experimental results are shown in form of a purely Standard Model measurement. The analyses that have been carried set up a path for future measurement at higher energies. It is also interesting to compare the results from the two experiments. Comparisons show clearly that tiny differences between different detector can lead to significant differences in the total amount of background for this measurement and in its physics composition. Special attention should be stressed on the efficiencies of lepton reconstruction a low transverse momenta and the resuting finite efficiency of the veto on additional leptons. These effects, virtually impossible to simulate using only commonly accessible simulation tools, are decisive for the amount of background coming from WZ pair production where one lepton from Z decay gets lost. It is these numbers that produce the lion's share of the overall differences between ATLAS and CMS results. Surely, background composition at 8 TeV and under the selection criteria that have been applied here to carry a Standard Model measurement is significantly different from the expected background composition at higher energies in a selected kinematic region optimized for the search for deviations from the Standard Model.

The idea of having an analysis of the non-resonant $W^{\pm}W^{\pm}$ process came into being in CMS largely due to my presentation at a CMS meeting on VV scattering held back in 2012 and the discussions that followed. I did not participate in the analysis of data taken by CMS which lay at the basis of the discussed paper.

Chapter 6 of the monograph, "What can the LHC measure", contains a personal-perspective attempt at answering the question of what will be possible to observe in VV scattering processes in experiments on the LHC operating at 13 TeV. All the relevant selection criteria discussed in the previous chapters that aim at isolating the most interesting events from the point of view of deviations from the Standard Model are here recapitulated on. For the $W^{\pm}W^{\pm}$ and $W^{+}W^{-}$ processes these are originally conceived selection criteria, while for $W^{\pm}Z$ and ZZ the selection criteria are inherited from earlier work by other authors, but independently cross-checked and confirmed by self-made simulations.

Subsequent sections 6.1 thru 6.6 present the general methodology of signal evaluation, where signal should be understood as the effect of non-standard Higgs to gauge couplings, and of the most important background sources: irreducible (by definition equal to the Standard Model), inclusive $t\bar{t}$ production, $W+$jets events, QCD multijet events and WZ pair production. Estimates are made such that a clear division is done between the effects of physics itself and the apparatus effects. The former can be simulated using publicly available event generators, regardless of specific detector details. Correct consideration of the latter requires full detector simulation for CMS or ATLAS, but to a first approximation these effects can be described by choice of a few numbers that are detector-specific and that will simply scale the relevant physics spectra. Numbers describing the b tagging efficiency, the efficiency of lepton sign determination at high p_T and the probabilities to reconstruct a jet, hadron or photon as an electron, were estimated based on available studies carried within the CMS experiment, discussed in section 4.7 (in case these numbers turn out to be wrong, it should be simple to rescale the result). Experimental resolutions in the measurement of electron, muon and jet transverse momenta were likewise taken into account. Other apparatus effects were neglected. Based on the above rules, the cross sections of the signal and each of the individual backgrounds can be calculated after each step of the full selection process, as well as the final lepton-lepton mass spectra (or missing mass spectra in the case of WZ and $ZZ \to 2l2\nu$) after the entire selection process (section 6.8). The general conclusion that arises from these results is still that the $W^{\pm}W^{\pm}$ process offers the best sensitivity to the Higgs couplings, but even in this case only relatively large deviations from the Standard Model (of order 0.8) could be observed and most likely not until the High Luminosity LHC phase.

Section 6.9 discusses expected effects related to anomalous gauge couplings described via effective dimension-6 operators. Having in mind the most up-to-date experimental limits on those operators (the latter coming also from measurements of anomalous triple couplings done by CMS and ATLAS, see Chapter 3), it turns out that the magnitudes of possible BSM effects are currently at the limit of sensitivity that can be achieved in the LHC at 13 TeV. However, at least one dimension-6 operator (traditionally scaled with coefficient c_{WWW}) can generate signal measurable still before the HL-LHC phase. More relevant from the point of view of the present work is nonetheless the question of separating different physics scenarios - in particular the signals of non-standard Higgs couplings from the signals of anomalous c_{WWW}. This is tightly connected to the polarizations of the $W^{\pm}W^{\pm}$ pair, since the dimension-6 operator scaled with c_{WWW} modifies only vertices involving transversely polarized gauge bosons, in contrast to the Higgs couplings. Section 6.9 shows that kinematic separation of these two types of signals based on the respective transverse momentum distributions of reconstructed tagging jets should be sufficient to assess the proper signal source, provided signal itself will be statistically significant and given an integrated luminosity of the order of 3000 fb^{-1}. Contributions of other operators may however blur the emerging picture.

All the simulation work referred to in sections 6.1 thru 6.9 has been done by myself or under my supervision. Most of these results have not been published yet.

Section 6.10 presents the expected effects related to anomalous quartic couplings decribed via effective dimension-8 operators. Only results for the $W^{\pm}W^{\pm}$ are here quoted. These are results of the work of other people, some on a phenomenological level and some including elements of apparatus effects, and even involving full detector simulation (ATLAS studies). They show the expected sensitivities to selected dimension-8 operators at the LHC assuming an integrated luminosity of 300 and 3000 fb^{-1}. Exisiting studies have a strongly selective character and there is still a long way before all the potential effects related to dimension-8 operators get fully understood. It should be stressed however that none of the existing analyses makes distinction between different polarizations of the $W^{\pm}W^{\pm}$ pair. Conversely, all of them assume a relatively high threshold on the transverse momentum of tagging jets. Since kinematic separation between W_LW_L and W_TW_X must be here as pronounced as it was in the case of anomalous dimension-6 operators, application of techniques to separate the helicities, as advocated in the present work, as well as additional work towards lowering the jet p_T thresholds, can be of special importance for the operators that modify W_LW_L pairs. All the quoted analyses could be worth reworking accordingly before the HL-LHC program starts.

Chapter 7 of the monograph, “Beyond the LHC”, sketches the perspectives of future VBS measurements, $W^{\pm}W^{\pm}$ in particular, in future hadron colliders that may become LHC successors. The Future Circular Colliders (FCC) project in its proton-proton option, supposed to provide a center of mass energy of 100 TeV, was taken as primary basis for further considerations. There exist no full simulations of VV scattering processes at 100 TeV so far, they will certainly be the subject of work for many people and many forthcoming years. This chapter shows a personal-perspective glance at the FCC physics capabilities based on original simulation work. The latter involved some preliminary analyses at the phenomenological level, following essentially the same guidelines as discussed before for 14 TeV except for taking into account the main kinematic differences induced directly by higher beam energy. Even considering that simulations carried entirely in the lowest order of QCD expansion may not be sufficient at such energy, a rough preliminary glance makes it clear that increasing the beam energy provides a qualitative leap in the sensitivity to any Beyond the Standard Model effects - whether coming from Higgs couplings or from pure gauge couplings. Assuming an integrated luminosity of the order of 1 ab^{-1}, the Higgs couplings can be independently determined to a couple of per cent. Moreover, kinematic separation of W_LW_L and W_TW_X processes based on transverse momentum spectra of tagging jets is here clear enough, so that the physical source of any observed deviations can be unequivocally identified. Likewise, the range of the lepton-lepton invariant mass that will be probed is wide enough to carry exact measurements of anomalous couplings responsible for the observed effects. Unlike the LHC which may or may not observe physics beyond the Standard Model, the FCC can without doubt be the machine to study the details of the theory that one day will replace it.

Chapter 8 contains a short summary of the main conclusions. The work ends with a comprehensive bibliography of the subject.

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