Attachment no. 3b to the "Wniosek o wszczęcie postępowania habilitacyjnego"
(Application for initiation of habilitation proceeding)
(file: MBluj_AutoreferatEN.pdf)

Warsaw, 10 April 2019

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Summary of research achievements

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1 Personal data

Surname and name: Michał Bluj

2 Education

2006: Ph.D. in Physics, Sołtan Institute for Nuclear Studies
Thesis title: *Poszukiwanie bozonów Higgsa w akceleratorach LEP i LHC*
(A search for the Higgs bosons at LEP and LHC colliders)
Supervisor: prof. dr hab. Ryszard Sosnowski
Reviewers: prof. dr hab. Elżbieta Richter-Wąs
dr hab. Aleksander Filip Żarnecki

2000: M.Sc. in Physics, Institute of Experimental Physics, University of Warsaw
Thesis title: *LEP jako narzędzie poszukiwania nowej fizyki*
(LEP as a tool for searching new physics)
Supervisor: dr inż. Piotr Zalewski

3 Employment

X 2006 – now: National Centre for Nuclear Studies, Associate Professor (*adiunkt*)
(on leave of absence: X 2007 – X 2013)

X 2008 – X 2013: Laboratoire Leprince-Ringuet (LLR) at École Polytechnique, Palaiseau, France, Postdoc

X 2007 – X 2008: Laboratório de Instrumentação e Fısica Experimental de Partıculas (LIP), Lisbon, Portugal, Postdoc

X 2005 – X 2006: Sołtan Institute for Nuclear Studies, Physicist
(current National Centre for Nuclear Studies)

X 2000 – X 2005: Sołtan Institute for Nuclear Studies, doctoral studies
(current National Centre for Nuclear Studies)

4 Academic career

My scientific work has been primarily related to the search for the Higgs boson (or bosons), and then after its discovery, to studies of its properties.

During my master studies at the Faculty of Physics of the University of Warsaw, I become interested in searching for the Higgs bosons - the last missing piece of the Standard Model of fundamental interactions. The existence of the Higgs boson (or bosons) is a consequence of the Brout-Englert-Higgs (BEH) mechanism, by which elementary particles (W and Z bosons and fermions) obtain mass while maintaining the gauge symmetry of the Standard Model [1, 2, 3, 4, 5]. The simplest variant of this mechanism is realized by using one doublet of complex scalar fields and predicts the existence of one neutral Higgs boson, the Standard Model Higgs boson. However, there is no strong justification for excluding more complex scenarios. One of the most frequently considered extended scenarios, motivated, on the one hand, by supersymmetric models and, on the other, by the rich phenomenology common to many extended models, is the two Higgs doublet model (2HDM). 2HDM predicts the existence of five Higgs bosons: three neutral and two charged.

In order to pursue my scientific interests, I started to work within a team coordinated by Piotr Zalewski, belonging to the Warsaw Group of the DELPHI experiment at the LEP collider at CERN, searching for Higgs bosons predicted by extensions of the Standard Model.

The time of my master studies, academic years 1998/1999–1999/2000, fallen on the last period of LEP operation, when electrons and positrons have been collided with the highest achievable energy of approximately 200 GeV. The data collected by four LEP experiments (ALEPH, DELPHI, L3 and OPAL) in this time allowed to exclude the existence of the Higgs boson of the Standard Model with the mass below 114.4 GeV at the 95% confidence level [6].

In parallel to searches for the Standard Model Higgs boson and the Higgs bosons predicted by the Minimal Supersymmetric Standard Model (MSSM), also searches for Higgs bosons in the frame of the generalized extended models have been carried out. In the DELPHI experiment one of the leading groups in this field was P. Zalewski's team, of which I was a member. As part of my M.Sc. thesis, in addition to technical work as the production of Monte Carlo samples, I have developed a search in topologies produced by the cascade decays of the Higgs bosons. Such decays can be dominant when the decays of the heavier Higgs bosons into the lighter ones are kinematically allowed. When the lightest Higgs bosons decay into pairs of b quarks (the heaviest kinamatically accessible fermions), which is true in a wide range of 2HDM parameters, one obtains final states with at least four such quarks. The kinematic properties (topology) of such final states strongly depend on the masses of the Higgs bosons (and their differences), so it was crucial to create a signal-sensitive variable regardless of the topology. This was done using a decision tree[1]. The signal was not observed, therefore the exclusion limits on the product of the production cross sections and branching ratios were determined for each process analysed as a function of masses of the Higgs bosons [7]. These limits were presented in a way that was as model independent as possible, which allowed for easy interpretation of the limits in various models. This (at that time) innovative way of presenting results was developed (with my active participation) in discussions with theoreticians from University of Warsaw (namely with Maria Krawczyk and Jan Kalinowski). Results of my M.Sc. thesis (with other results obtained by the team) were made public as a note of DELPHI experiment for the Summer conferences in 2001 [8].

I was developing the searches for Higgs bosons in general models using DELPHI data also during the first period of my doctoral studies [9]. The final achievement of this research was a note of the DELPHI experiment for Summer conferences in 2003 [8] which then became the (peer reviewed) publication of the experiment [10]. This publication is one of the contributions to the final publication of the LEP experiments on the search for non-standard Higgs bosons [11] and the final DELPHI publication on this subject [12]. The paper [10] has been cited several dozen times.

During my doctoral studies, I joined the Warsaw Group of the CMS experiment (being designed at that time) on the Large Hadron Collider (LHC), which replaced LEP. The LHC was designed to discover (or exclude the existence of) the Standard Model Higgs boson with a mass ranging from approximately 110 GeV, i.e. from a mass range excluded by LEP experiments, to approximately 1000 GeV given by general theoretical considerations on stability of the model. Involvement in the CMS experiment allowed me to continue my research on the Higgs boson.

During this period, I joined an international working group of theoreticians and experimentalists working on phenomenology of non-standard (extended) models of the Higgs sector and related experimental strategies. The result was CERN Yellow Report which I co-authored [13]. My contribution to this activity was a study on the problem of determining the CP parity of the Higgs boson using angular correlations in the $\mathrm{H} \rightarrow ZZ \rightarrow 4\ell$ process with the CMS detector. Determination of CP parity was based on minimizing the likelihood function which linked the measured angles with the parameters of the Lagrangian describing the process. This analysis is the second part of my Ph.D. thesis [9] and was included in the Physical Technical Design Report (PTDR) of the CMS experiment [14].

At the same time, I have been involved in the development of a first level muon trigger of the CMS detector for which the Warsaw Group was responsible. This system, called PAC (pattern comparator), was designed to reconstruct online, i.e. in real time the transverse momentum of muons by comparing the signal from resistive plate chambers (RPC) to previously generated patterns[2]. Additionally to trigger, the PAC included a data acquisition system for RPC. The PAC was the first part of a muon triggering system, whose are an important signature in physical analysis at hadron colliders (in particular these concerning the Higgs boson).

I made the biggest contribution to the development of the PAC system, after defense of my Ph.D. thesis, during a series of tests called the Magnet Test and Cosmic Challenge (MTCC) in 2006/2007. The tests have been performed using a fully equipped slice of the CMS detector located on the surface, above the target installation site, with muons from cosmic rays [15]. The PAC system itself as well as its interoperability with other CMS systems have been tested. Both cosmic rays and specially prepared

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[1] It was not, however, a decision tree in the sense of modern multivariate analysis (MVA) techniques optimized by machine learning.

[2] The PAC system together with other first-level triggers was replaced by more modern solutions in the years 2015–2016. In particular, the Warsaw Group has designed and is responsible for one of the new level-1 muon triggers.

test data have been used for the PAC tests [16, 17, 18, 19]. These works were awarded by the director of the Sołtan Institute for Nuclear Studies as one of the most important achievements of the institute in 2006.

In Fall 2007, I began a one-year postdoctoral internship at the Laboratório de Instrumentação e Fısica Experimental de Partıculas (LIP) in Lisbon (Portugal). During this period, I have been involved in the preparation of the measurement of cross section for the $t\bar{t}$ pair production using the final states with tau lepton. During my stay at LIP, I managed to create a basis of the analysis which was later published as a note of the CMS Collaboration [20]. In addition, I have been involved in the work on data analysis tools, common to the CMS Collaboration, in particular related to the identification of tau leptons.

In Fall 2008, I was invited to a two-year-long postdoctoral internship at Laboratoire Leprince-Ringuet (LLR) at the École Polytechnique in Palaiseau (near Paris), then extended for another three years. In that time, I have been involved in studies on reconstruction algorithms and analyzes using particles provided by the "particle-flow" reconstruction [21], in whose development the CMS group at LLR has been involved. In the particle-flow approach, measurements made with the use of individual subdetectors (tracks, energy deposits in calorimeters and signals in muon chambers) are correlated with each other in order to optimally reconstruct and identify all particles in the final state. Then, from such reconstructed particles, „complex objects" are built: quark and gluon jets, tau leptons in decays into hadrons (and neutrino)[3], missing transverse momentum (signal of neutrinos or other hypothetical particles not interacting with the detector material), and determined electron and muon isolation.

When I started my internship at LLR, the first version of the particle-flow was ready, but without electron reconstruction fully integrated into it. In addition, the particle-flow approach was not widely accepted within the CMS Collaboration. Therefore, goals set for me were: firstly to demonstrate with a realistic analysis that usage of particle-flow improves its sensitivity and secondly to help understand the electron reconstruction. The benchmark analysis chosen for this purpose was search for the Higgs boson decaying to tau pairs and produced via vector boson fusion (VBF) process. It was found that usage of particle-flow reconstruction indeed improved the analysis thanks to better energetic and angular resolution of missing transverse momentum, jets and tau leptons than provided by subdetector-based reconstruction approach (despite simple reconstruction of tau leptons). This started my search for the $\mathrm{H} \rightarrow \tau\tau$ decay. What concerns electrons, I have been studied the particle densities around electrons (isolation) which study contributed to better account of bremsstrahlung photons in the electron reconstruction. The study was firstly performed with simulated events and then (in 2009–2010) with first proton-proton data collected by the CMS detector [22, 23, 24].

In the course of development of the $\mathrm{H} \rightarrow \tau\tau$ search, I have been involved (and I am involved until now) in development of algorithms for identification of hadronic decays of tau leptons and preparation of high-level triggers (HLT) for final states with tau leptons. In particular, I have been a convener (and an active member) of Tau Trigger Group, responsible for such triggers, in years 2011–2015, i.e. a difficult period when the luminosity provided by LHC increased by an order of magnitude. This required continuous prompt adjustments and improvements of the triggers, whose have been achieved thanks to integration of the particle-flow algorithms in HLT. What concerns identification of tau leptons, I was one of proponents of algorithms in which individual decay modes of tau lepton are reconstructed using particles provided by particle-flow. One of such algorithms (combining ideas of several people), called HPS (hadrons-and-strips) become eventually the official algorithm of the CMS Collaboration [25].

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[3] The decays of tau leptons to electrons and muons are reconstructed by the reconstruction algorithms for these leptons.

In parallel, the H → $\tau\tau$ analysis have been developed and incoming data analyzed with my involvement (I was a leader of a team at LLR working on the subject[4]). It has been marked by successive milestones: the first measurement of the Z bozon cross section in its decays to $\tau\tau$ pairs by CMS with 2010 data [26], the search for the H → $\tau\tau$ decay contributing to the discovery of the Higgs boson in 2012 [27], and the evidence of the H → $\tau\tau$ decay with full data collected in 2011–2012 (Run-1) [28]. My key contribution was a proposal (made independently by a few people) of considering in the analysis events not passing selections specific for the VBF production and containing at least one jet. Such events are produced in the gluon fusion process (main production mode of the Higgs bozon at LHC) with the jet being radiated from the initial state. Presence of the jet enhances the signal to background ratio compared to events selected without requiring jet presence, and introduce the Lorentz-boost to the $\tau\tau$ system, i.e. the system has nonvanishing p_{T}, which improves resolution of reconstructed mass of the system.

In 2011–2012, I have been a coordinator of bilateral cooperation between CMS groups at LLR and in Warsaw (Faculty of Physics at University of Warsaw and National Centre for Nuclear Studies) in the frame of French-Polish cooperation called COPIN (from French side)[5]. Cooperation facilitated scientific and personal exchange between groups, for instance allowed for a few-month-long internship at LLR for a doctoral student from Warsaw (T. Früobes).

I Fall 2013, I went back to my mother institute (National Centre for Nuclear Studies) continuing engagement in both reconstruction of tau leptons and studies on the H → $\tau\tau$ decay with CMS.

In 2015, I was nominated (for two years) a convener of the Tau Physics Object Group (Tau POG), an important management position in the CMS Collaboration, to lead the group of people developing, maintaining and validating the tau identification algorithm. As the covener I was one of main authors of a reference publication on tau identifiaction algorithm at CMS for LHC Run-2 [29].

In 2015, I obtained a three-year (extended for a year) OPUS grant funded by the National Science Center (Poland) no. 2014/13/B/ST2/02543, entitled *"Decays to tau leptons – a tool to probe properties of the Higgs boson using the CMS experiment at LHC"*[5]. Under this grant, a research group formed by five people (from National Centre for Nuclear Studies and Faculty of Physics at University of Warsaw) has been developing experimental methods related to the identification of tau lepton and to the triggering events with tau leptons, as well as the analysis that eventually led to the observation of the H → $\tau\tau$ decay by the CMS experiment [30].

In parallel, I have join an activity of Warsaw CMS Group related to the development of a new first level muon trigger of the CMS detector, coordinated by Marcin Konecki. In particular, I have proposed an algorithm to remove duplicates of reconstructed single muons.

Finally, I have been selected several times to present physics results on behalf of the CMS Collaboration at international conferences[5]. I have been also active in the internal analysis review committees of the collaboration, as an expert of tau identification, particle-flow reconstruction and in general analysis methods.

Additional information regarding the details of my educational achievements, scientific cooperation at national and international level, presentations given at international conferences, etc. are presented (in Polish) in the attachment no. 5 titled *"Informacje dodatkowe o dorobku"* (file: MBluj_DodatkoweInfo.pdf).

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[4] The team was composed with one or two postdocs and two or three doctoral students.

[5] Details on projects in which I have been participated and on presentations I have given at international conferences are presented (in Polish) in the attachment no. 5 entitled *"Informacje dodatkowe o dorobku"*, file: MBluj_DodatkoweInfo.pdf.

5 Presentation of the scientific achievement

in accordance with Polish regulation Art. 16, Par. 2 of the Act of 14 March 2003 on Academic Degrees and Title, and Degrees and Title in the Arts (Dz. U. 2017 r. poz. 1789)

As the scientific achievement I present a monograph entitled:

From the τ lepton reconstruction to the observation of the Higgs boson decay to $\tau\tau$ pairs with the CMS experiment at LHC
(in Polish: *Od rekonstrukcji leptonu τ do obserwacji rozpadów bozonu Higgsa na pary $\tau\tau$ w eksperymencie CMS przy LHC*,

released (in Polish) by the National Centre for Nuclear Research Publishing, Świerk, 2019,
ISBN 987-83-941410-8-0, of which I am the sole author.

The presented monograph is devoted to the reconstruction and identification of tau leptons (in their decyas to hadrons and neutrinos) in the CMS experiment, and to the search for the $\mathrm{H} \to \tau\tau$ decay using this experiment. This subject reflects of the research I have undertaken after obtaining my Ph.D.

The monograph is opened by a brief historical outline presenting the discovery of tau lepton by Martin Perl and his team. This is a textbook example of an analysis that led to a discovery and subsequent confirmation of the identity of a new particle. In addition, the Mark I detector, with which the taon was discovered (and the J/ψ meson), was one of the first detectors composed of (electronic) subdetectors of various types that form subsequent layers that cover the full solid angle around interaction point, which allows the identification of particles of different types. As such, it has become the progenitor of most modern universal detectors used in high-energy physics, including the CMS detector.

The first part of the monograph discusses the construction of the CMS detector (Chapter 1) and the reconstruction of events collected by the CMS detector (Chapter 2). Particular attention is devoted to the novel "particle-flow" reconstruction approach [21], in which development I had contributed. In this approach, the flow of particles through the detector is (somehow) followed from the interaction point by the tracking detector and calorimeters up to the muon chambers (hence the name of the method) in order to link individual tracks with deposits in calorimeters and signals in muon chambers for optimal and consistent reconstruction and identification of all particles in the final state (electrons, muons, photons, and charged and neutral hadrons). The particles reconstructed in this way are then used to reconstruct the jets resulting from the fragmentation of partons (quarks and gluons), tau leptons in their decays to hadrons (and neutrinos), determine the missing transverse momentum, and to define the isolation of electrons and muons.

The second part of the monograph is dedicated to the reconstruction and identification of tau leptons in their decays to hadrons and neutrinos (denoted τ_h). The main challenge in identification of τ_h is to distinguish them from jets from the fragmentation of quarks and gluons, which are copiously produced in proton-proton collisions. In some analyzes, the misidentification of electrons or muons as τ_h candidates may also be a significant background that must be suppressed. Access to particles reconstructed by the "particle-flow" allows identification of individual products of the τ_h decays, and then definitions of discriminators of misidentified jets, electrons and muons based on the distribution and properties of the particles around these decay products. This approach (of which I was a co-author) is the basis of the HPS (hadrons-plus-strips) algorithm developed in the CMS experiment [25,29], which is discussed in Chapter 3.

The HPS algorithm reconstructs individual decays of tau leptons to hadrons starting from the components of jets built of particle-flow particles. The final states of the taon decays contain charged hadrons and neutral pions. The latter immediately decay to pairs of photons, which have a high probability to convert to e^+e^- pairs in the material of the tracking detector. The strong field of the CMS detector magnet leads to the spatial separation of the e^+e^- pairs in the η–ϕ (pseudorapidity–azimuth) plane. Therefore, to reconstruct the full energy of neutral pions, electrons and photons falling into the longitudinal region of $\Delta\eta \times \Delta\phi$ are clustered to form a "strip". Then, the HPS algorithm creates all possible combinations of charged hadrons and strips corresponding to the main decay channels of taon: $\mathrm{h}^\pm$, $\mathrm{h}^\pm\pi^0$ and $\mathrm{h}^\pm\pi^0\pi^0$ (unified to $\mathrm{h}^\pm\pi^0$s), and $\mathrm{h}^\pm\mathrm{h}^\mp\mathrm{h}^\pm$. They represent 57% of all decays of τ and 88% of decays to hadrons[6]. It is required that all hadrons forming the τ_h candidate are collimated, i.e. contained in a narrow cone, and that their invariant mass is consistent with the mass of $\rho(770)$ or $\mathrm{a}_1(1260)$ resonance for the $\mathrm{h}^\pm\pi^0$ or $\mathrm{h}^\pm\pi^0\pi^0$ and $\mathrm{h}^\pm\mathrm{h}^\mp\mathrm{h}^\pm$ hypotheses, respectively. Finally, the combination with the highest p_T is selected from all created. The distribution of the reconstructed mass of the τ_h candidate measured in the $\mathrm{Z}/\gamma^* \to \tau\tau$ events is shown in Fig. 1. In the figure, events with genuine τ_h are divided depending on the reconstructed decay channel: for the $\mathrm{h}^\pm\pi^0$ decay the τ_h mass distribution has, as expected, a (wide) peak corresponding to the $\rho(770)$ mass, and in the $\mathrm{h}^\pm\mathrm{h}^\mp\mathrm{h}^\pm$ decay to the $\mathrm{a}_1(1260)$ mass, while the candidates in the $\mathrm{h}^\pm$ decay channel have assigned mass of the charged pion.

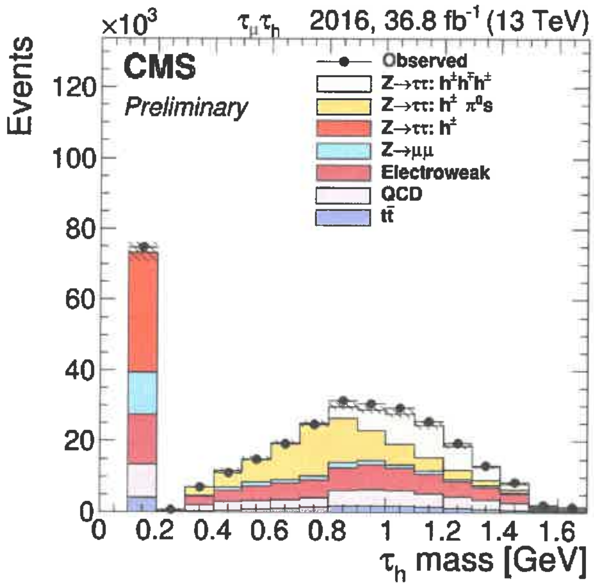

Figure 1: The distribution of the reconstructed mass of the τ_h candidate measured with $\mathrm{Z}/\gamma^* \to \tau\tau$ events that decay to the $\mu\tau_\mathrm{h}$ final state. The points correspond to the observed data while the filled histograms to the simulated $\mathrm{Z}/\gamma^* \to \tau\tau$ events divided depending on the τ_h decay channel and to the background processes with a jet or a muon misidentified as τ_h [31].

After the reconstruction of the decay channel, the τ_h candidate undergoes a series of identifications to suppress the background from misidentified jets, electrons and muons. These identifications are based on the distribution and properties of the particles around the reconstructed τ_h candidate. Discriminants of misidentified jets and electrons are created using multivariate analysis (MVA) techniques. The total efficiency of reconstruction and identification of τ_h using the HPS algorithm is, depending on the selected working point, between 30 and 70% with the probability of misidentification of jets, electrons

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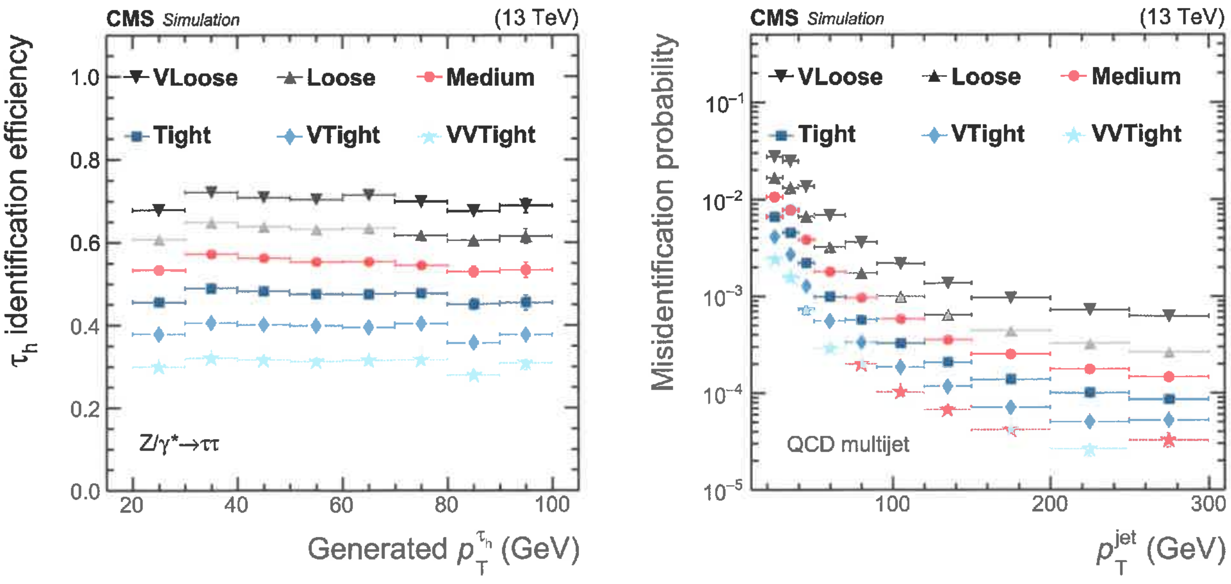
[6] See footnote 3.

and muons as τ_h of $\mathcal{O}(10^{-3})$, as illustrated in Fig. 2.



a) b)

Figure 2: The efficiency of the τ_h identification, estimated with simulated $Z/\gamma^* \to \tau\tau$ events (a), and the probability of misidentification estimated with simulated multijet events (b) for different working points of the HPS algorithm. The efficiency and probability of misidentification are shown in the function p_T of the generated τ_h and p_T of jet, respectively [29].

Then, in Chapter 4, tests of various aspects of the HPS algorithm, performed with data collected by CMS, are presented. The results of the tests show a good agreement with the expectations obtained with the simulation. For example, Fig. 3 shows the ratio of the efficiency of a commonly used working point (Tight) of the τ_h identification measured in data to expectations from simulation.

The next chapter (Chapter 5) covers the CMS detector triggering algorithms for events with tau leptons in the final state (for which I has been responsible) and the performance of these algorithms measured in the data collected by CMS.

Chapter 6 contains a summary of the second part of the monograph which discusses the methods of identifying τ_h in the trigger system and in the final event reconstruction of the CMS experiment.

The third part of the monograph is devoted to the analysis of the data which led to the observation of the decay of the Higgs boson to tau lepton pairs at CMS. The $H \to \tau\tau$ decay channel is especially interesting because it is the second (after $H \to b\bar{b}$), in terms of the branching fraction, decay channel into fermions. Considering the fact that search for decays to $b\bar{b}$ pairs is especially difficult at hadron colliders, it is the $\tau\tau$ channel where the first direct observation of the Higgs boson coupling to the fermions has been expected. And, it actually happened in 2016[7].

The first chapters of this part of the monograph introduce the topic of the Higgs boson: Chapter 7.1.1 recalls the basic facts of the Higgs boson, and Chapter 7.1.2 presents the main aspects of the phenomenology of the Higgs boson at the LHC together with an outline of the analyzes that led to its discovery in 2012 [32, 27].

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[7] Independent observations of the $H \to \tau\tau$ decay were made by the ATLAS and CMS experiments using data collected in 2016, with the publication of CMS dated to 2017 and ATLAS to 2018. However, the combination of data collected by these experiments in 2011–2012 (Run-1) also resulted in observation of this decay.

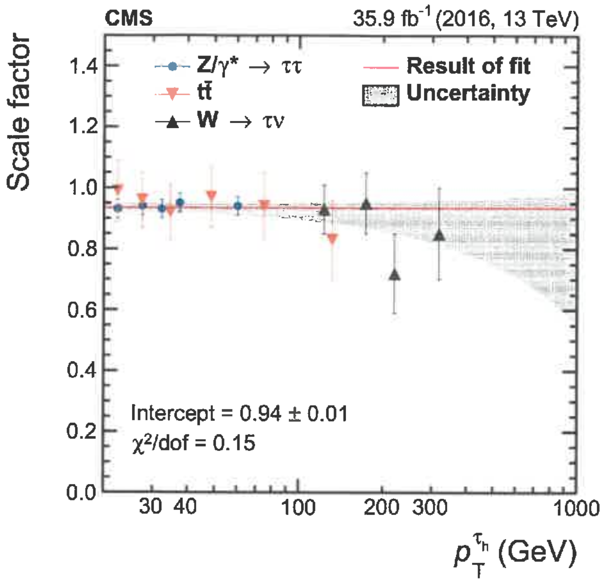


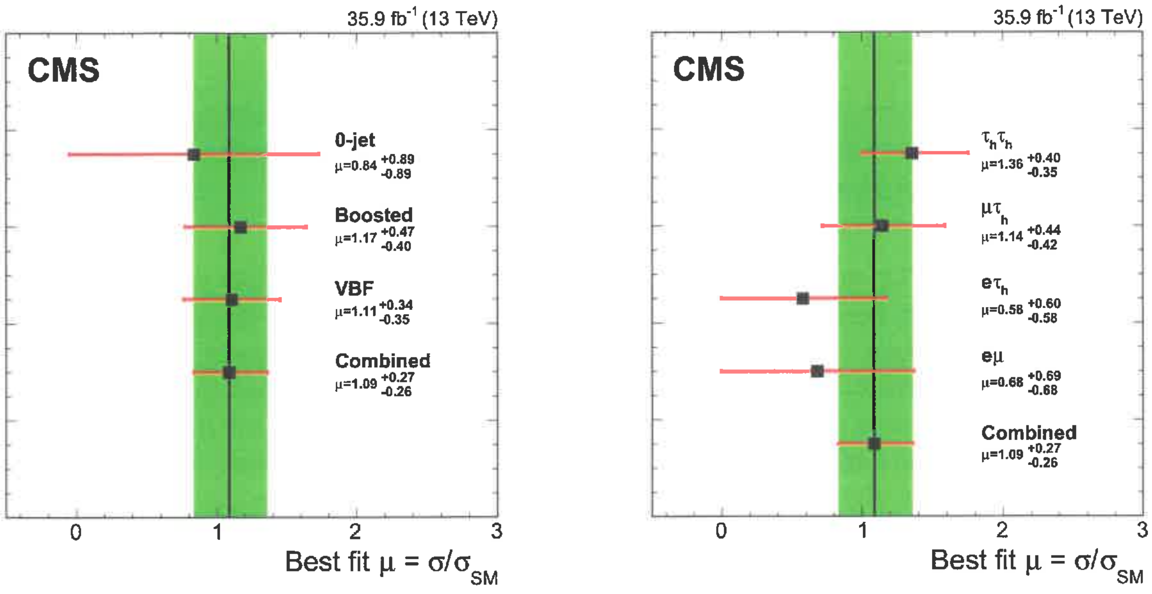
Figure 3: Factor scaling the identification efficiency of τ_h expected in simulation to the one measured in data, for the Tight work point, in the function of $p_T^{\tau_h}$. The measurements have been made using the $Z/\gamma^* \rightarrow \tau\tau$, $t\bar{t} \rightarrow \mu\tau$+jets and $W \rightarrow \tau\nu$ events [29].

Then, in Chapter 7.2 the search strategy for the $H \rightarrow \tau\tau$ decay in CMS is discussed. This strategy is, on the one hand, determined by the fact that tau leptons decay in the detector in many channels, producing both lighter charged leptons and hadrons, which leads to many possible final states. The second factor influencing the strategy are additional particles (to the tau decay products) in the final state, which are related to the Higgs boson production mechanism. Their presence and characteristics allow better discrimination of the signal (production of the Higgs boson) from the background, i.e. processes leading to the final state mimicking the signal. In early studies, i.e. before launching the LHC, the search strategy in the $H \rightarrow \tau\tau$ channel used only the specific features of the vector boson fusion (VBF) Higgs boson production mechanism: the existence of two jets separated in pseudorapidity, with strongly suppressed hadron activity between them. Later, during the analysis of early CMS data (collected in 2011), an event category with one jet and a complementary category without jets were added. They are sensitive to the dominant production process of the Higgs boson – the gluon fusion ($gg \rightarrow H$). The creation of two categories sensitive to the $gg \rightarrow H$ process instead of the inclusive one (which I was one of the proponents) is motivated by the observation that the cross section of the Higgs boson production decreases slower with p_T of the additional jet (emitted from the initial state) than the cross sections of the main background processes. This results in higher purity (and therefore sensitivity) than for one inclusive category. In addition, the presence of a jet means that the Higgs boson has a non-zero transverse momentum (balancing p_T the jet) which improves the resolution of the reconstructed mass of the $\tau\tau$ pair, which is the main variable that distinguishes the signal and background. Finally, the presence of an additional lepton (electron or muon) or a pair of the leptons can be a signal of the leptonic decays of W and Z bosons produced together with the Higgs boson. However, due to the small cross section of this production process, which is further suppressed by the requirement of a leptonic decay of W and Z bosons, its contribution to the final result of the search for decays $H \rightarrow \tau\tau$ is small (therefore, not discussed in the monograph).

Chapter 7.3 discusses the methods for determining the invariant mass of pair of taons using momenta of visible products of their decays and missing transverse momentum.

The following chapters present the actual analysis of CMS data: Chapter 7.4 discusses the event selection, Chapter 7.5 definition of event categories inspired by the production processes and depending on the number and kinematic properties of jets, and Chapter 7.6 methods for determining the expected background level. The discussion of systematic uncertainties and the results are presented in Chapters 7.7 and 7.8, respectively.

As a result of the analysis of $36\,\mathrm{fb}^{-1}$ of data collected by the CMS detector in 2016, a significant excess of events above expectations for the background of 4.9 standard deviations (4.9σ) was observed for the mass of the Higgs boson of $m_{\mathrm{H}} = 125.09\,\mathrm{GeV}$, with a corresponding expected significance of 4.7σ [30]. Signal strength, i.e. the ratio of the measured and expected product of the cross section and the branching ratio, which best describes the data is $\mu = 1.09^{+0.27}_{-0.26}$. Signal strength values obtained independently for individual event categories and final states are consistent with each other and the global value, which proves the compliance of the excess with the hypothesis of the $\mathrm{H} \to \tau\tau$ decays (Fig. 4). When the results of the 2016 data analysis is combined with the result of the Run-1 data analysis (2011–2012), in which an excess of significance of 3.2σ was observed, a significance of 5.9σ is obtained which exceeds commonly accepted observation threshold ($>5\sigma$). The combined significance corresponds to the signal strength of $\mu = 0.98 \pm 0.18$.



a) b)

Figure 4: Values of the signal strength (μ) obtained independently in event categories (a) and final states (b) assuming $m_{\mathrm{H}} = 125.09\,\mathrm{GeV}$. Global value of the signal strength (“Combined”) obtained in all event categories and final states amounts to $\mu = 1.09^{+0.27}_{-0.26}$ [30].

Finally, thanks to the combination of CMS measurements including all decays of the Higgs boson available at LHC (including the $\mathrm{H} \to \tau\tau$ decay) it was possible to determine the ratio of measured and expected coupling of the Higgs boson and tau lepton (κ_τ). The measured value of this parameter is $\kappa_\tau = 1.01^{+0.16}_{-0.20}$ and is consistent with unity expected in the Standard Model [33].

The last chapter of the monograph (Chapter 8) contains a summary and outlines directions of future developments of analyzes of the $\mathrm{H} \to \tau\tau$ decay and the contribution that the analyzes can make to the study of the Higgs boson properties.

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