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Habilitation review of the scientific, didactic and popularization achievements of Dr. Michał Bluj Associate Professor (adjunct) of the National Centre for Nuclear Physics in Warsaw

In response to the letter of the Central Commission for Degrees and Titles (No. BCK-V-L-9116/19) appointing me to the habilitation committee as a referee and to the invitation letter of the Secretary of the Scientific Counsil of the National Centre for Nuclear Physics in Warsaw, dr. hab. Aneta Malinowska, I present my review on the scientific achievements summarized in the monograph entitled

"From the τ lepton reconstruction to the observation of the Higgs boson decay into $\tau\tau$ pairs at the CMS experiment at LHC"

as well as on the academic, didactic and organizational accomplishments by Dr. Michał Bluj, a researcher of the National Centre for Nuclear Physics in Warsaw.

Formal assessment of submitted documentation

The documentation submitted by Dr. Michał Bluj has been prepared correctly and meets the requirements of :

- the Act of 14 March 2013 on academic degrees and scientific titles, (Dz. U. z 2017 r. poz. 1789),
- the Art. 179 paragraph 2 of the Act of July 3, 2018 "Przepisy wprowadzające - Prawo o szkolnictwie wyzszym i nauce" (Dz. U. z 2018 r. poz.1669)

- the Regulation of the Ministry of Science and Higher Education of 01/09/2011 regarding criteria for assessing a person's achievements applying for the conferment of the degree of habilitated doctor (Dz. U. 196 poz. 1165) and the ordinance of the Ministry of Science and Higher Education of 19.01.2018 on the detailed procedure and conditions for conducting activities in doctoral dissertations, in the habilitation procedure and in the procedure for obtaining the title of professor (Dz. U. z 2018 poz. 261).

General information about the candidate

Dr. Michał Bluj works at the National Centre for Nuclear Physics in Warsaw, currently as an assistant professor (adjunct), and earlier, from October 2005 to October 2006, as a Researcher. He graduated in physics in 2000 at the Institute of Experimental Physics, University of Warsaw, and then completed his doctoral studies at the Sołtan Institute for Nuclear Physics with a public defense of a thesis in June 2006. The doctoral dissertation was written under the supervision of Prof. Dr. Hab. Ryszard Sosnowski.

From October 2007 to October 2013 he completed two postdoctoral internships: first, a one-year postdoctoral training at the Laboratorio de Instrumentacao e Fisica Experimental de Particulas in Lisbon (Portugal), and then a two-year postdoctoral internship (extended to five-year) at the Laboratoire Leprince-Ringuet of the Ecole Polytechnique in Palaiseau (France).

From the very beginning of his scientific career, Dr. M. Bluj was involved in experimental activities related to the search of the Higgs boson and later to the study of its properties. During his master studies Dr. M. Bluj was involved, as a member of the Warsaw Group of the Delphi experiment , in the search of the Higgs boson using DELPHI data. Then during the doctoral studies Dr. M. Bluj joined the Warsaw Group of the CMS experiment and continued his previous research activity on the search for Higgs boson in the framework of the CMS experiment.

Then, after his PhD, dr. M. Bluj was involved in the development of a first level muon trigger of the CMS detector. A bit later he devoted himself to search of the $H \rightarrow \tau\tau$ decay at CMS. Together with the development of a new muon trigger of the CMS detector, the analysis of

this decay channel as well as the tau-lepton reconstruction and identification are the current subjects of Dr. M. Bluj' research.

Evaluation of the scientific achievements presented in the monograph

The scientific achievements are presented in the form of a monograph issued by the National Centre for Nuclear Research, Otwock-Świerk, in 2019. The dissertation concerns two aspects of the leading themes of modern experimental particle physics: the first one is the reconstruction and identification of particles, in particularly the tau-lepton reconstruction, at CMS, the second one, related to the Higgs boson study, is the search for the $H \rightarrow \tau\tau$ decay at CMS. The monograph, consisting of 131 pages in total, is written in Polish and includes the main text, a table of contents, an introduction, a list of abbreviations. The main text terminates by a section summarizing the main results and discussing the perspectives of the $H \rightarrow \tau\tau$ decay study at LHC.

The monograph can be divided in three parts.

In the first part, that includes two sections, the author briefly describes the Large Hadron Collider (LHC) as well, more in details, the technical details of the CMS detector of the collider, such as the silicon tracker, the calorimetric systems, the muon spectrometer and the trigger (Section 1), whereas Section 2 outlines the particle-flow (PF) reconstruction algorithm. The PF reconstruction was first derived and applied at the ALEPH experiment of the LEP collider. The first application of the PF reconstruction approach was done in 2009 by the CMS experiment. So. the PF algorithm was first studied using Monte Carlo events in 2009 and then applied in physical analysis to the identification and reconstruction of all final-state particles in 2010. A key component for the PF reconstruction is the fine spatial granularity of the detector layers and it was proven that the CMS detector is very suitable for the application of the PF algorithm. In order to reconstruct and identify all final particles (electrons, muons, photons, charged hadrons) the global event description was applied. Then, having identified the final particles, the superior "complex objects" (quark and gluon jets, tau-leptons) can then be reconstructed.

In the second part of the thesis the author outlines the PF algorithm of identification and reconstruction of the 'hadronic' tau-lepton, i.e. events

in which tau-leptons decay in (*hadrons* + ν_τ), (the so called Hadrons-And-Strips (HPS) algorithm described in Section 3) and its application for the CMS data (Sections 3-6). As tau-leptons are very short lived particles, they can be reconstructed by their "visible" decay products (mainly, charged hadrons and neutral pions). The charged hadrons are reconstructed using their associated tracks in the inner tracker. The neutral pions decay virtually into photons which, in turn, can convert in eletron-positron pairs, and, finally, electrons after passing the magnetic field, cluster with photons making "strips" in the $\eta - \varphi$ plane As already mentioned, the performance of the HPS algorithm is presented in Section 3. Application of the HPS algorithm and tests of tau-lepton identification in the CMS data from 2016 are presented in Section 4. In Section 5 the performance of 'hadronic' tau-lepton' identification in the high-level trigger is discussed, whereas Section 6 summarizes the state of art in the tau-lepton identification at CMS discussed in Sections 3-6.

The last part, Section 7, provides an overview of the search for $H \to \tau\tau$ performed with the data collected by the CMS detector at center-of-mass energies of 7 and 8 TeV. In fact, of the available Higgs' decay modes, the most promising is the decay to a pair of tau-leptons (τ), which balances a modest branching ratio with manageable background. Aspects like the current status of the Standard Model, the Higgs production mechanism and its main decay modes are discussed in the first subsection. The next subsections are devoted to study of the $H \to \tau\tau$ decay mode at CMS and discuss among others the search strategy, the tau-pair invariant-mass reconstruction, the categorization of events. Special attention was focused on the $Z/\gamma^* \to \tau\tau$ and W+ jets background estimation. Finally, the observed and predicted tau-pair invariant-mass for the signal and background processes are collected in the last subsection. The best fit of the signal strength is compatible with one as predicted by the SM .

Summarizing this part of my report: the scientific level of the dissertation is very high, its aims and the results obtained very clearly and comprehensively presented. The materials is presented in an instructive and logically consequential way, bringing to the final results in Section 7.8. In fact, the author has taken an active role in all subjects presented in the monograph:

- He was involved in the development of the muon pattern comparator of the CMS detector (Section 1), and later in tests of the comparator with cosmic rays muons.

- For the PF reconstruction algorithm Dr. M Bluj has contributed to the study related to the electron (Section 2) and tau-lepton reconstruction (Section 3).
- Moreover, the habilitant was involved in the preparation of the high-level-triggers that allows to carry out tau-lepton identification by the HLS method (Section 3).
- Since 2010 Dr. M. Bluj has participated in the development of the CMS triggering algorithms for events with tau-leptons in the final state (Section 5) and, finally, in 2015 was nominated convener of the Tau Physics Object Group, a group that develops, maintains and validates the tau identification algorithms at CMS.
- Also worth mentioning is the embedding method used in the $H \to \tau\tau$ analysis developed by Dr. T. Fruboesa in collaboration with Dr. M. Bluj (Section 7).

The monograph indirectly indicates the elements of analysis in which the author was directly involved and the innovative elements of his contribution. This latter is confirmed by the support letter of the CMS Spokesperson Prof. Roberto Carlin, who has appreciated Dr. M. Bluj' work and states that he was able to propose new techniques related to the PF reconstruction algorithm, successfully implemented his ideas and brought the analysis to the stage of final publications for the collaboration.

Assessment of scientific and research as well as didactic activities

The validity of Dr. Michał Bluj's scientific activity is recognized by the international community and is proved by the large number of citations: 41989 in total (34818, excluding self-citations) of the 941 scientific articles in (co)-authorship and Hirsch index of 92. For the 38 articles Dr. M. Bluj 's contribution is stated as significant. Recognizing his experience, the CMS collaboration appointed him as convener of the Tau Trigger Group for 2011 – 2015, and then in 2015 as convener of the full Tau Physics Object Group, i.e. as a leader of the group developing and maintaining the tau-lepton identification algorithm of CMS. Also Dr. Bluj was selected to present the research results on behalf of the CMS collaboration in international conferences, in particular in eight talks related to the habilitation subject.

Dr. M. Bluj's work in the CMS collaboration is recognized in the support letter of CMS Spokesperson Prof. Roberto Carlin who characterizes him as the one who "gave very significant original contributions to the algorithms of the successful reconstruction methodology of CMS, the particle-flow, and in particular to the reconstruction of tau leptons" events. Dr. M. Bluj' work was also recognized by the Polish National Science Centre, as being among the winners of the OPUS grant of the year 2014. He also participated in several research projects related with the CMS physics.

Being involved in international cooperation as a member of the CMS collaboration, Dr. M. Bluj has acted as a coordinator of the bilateral cooperation between CMS group at the Laboratoire Leprince-Ringuet (France) and the group in Warsaw. Also, he was invited to give seminar presentations in several European universities and research institutes.

Against the background of such large and notable scientific activity, the didactic activity of Dr. M. Bluj is more modest. This is clearly related to the fact that the whole of his scientific activity after the MSc degree took place in research institutes. It should be noted, however, that Dr. M. Bluj was involved in the supervision of students for their pre-master internships (two at the National Centre for Nuclear Physics in Warsaw and two at the Laboratoire Leprince - Ringuet, Palaiseau, France). Also in the years 2012–2014 Dr. M. Błuj worked directly with the four foreign students participating in the $H \rightarrow \tau\tau$ decay search within the French-Polish initiative COPIN. In addition, Dr. M. Bluj is the second supervisor of the PhD thesis of Michał Olszewski (University of Warsaw).

Summary

I believe that Dr. M. Bluj's monography entitled **"From the τ lepton reconstruction to the observation of the Higgs boson decay into $\tau\tau$ pairs at the CMS experiment at LHC"** makes a significant contribution to the development and validation of the tau-lepton identification algorithms and therefore can form the basis of the habilitation proceedings. Therefore his scientific achievements in the field of elementary particle physics, his participation in international cooperation as well as his didactic activity, in my opinion, fully satisfy the statutory requirements set for candidates applying for doctor degree Habilitated in the field "Natural

sciences”, discipline “physical sciences” (Dziedzina nauk ścisłych i przyrodniczych, nauki fizyczne) referred to in Art. 16 of the Act of March 14, 2003 on scientific degrees and scientific titles and on degrees and title in the arts (Art. 16 ustawy z dnia 14 marca 2003 r. o stopniach naukowych i tytule naukowym oraz o stopniachi tytule w zakresie sztuki, Dz. U. 2003 nr 65, poz. 595 z pózn. zm)

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