TO THE SCIENTIFIC COUNCIL OF THE FACULTY OF PHYSICS
UNIVERSITY OF BELGRADE

At the VIII session of the Scientific Council of the Faculty of Physics University of Belgrade, dated June 26th 2024, we have been appointed to be the members of the Committee for the assessment of the doctoral dissertation *Radiative W boson decay studies and the upgrade of the ATLAS muon spectrometer readout system* submitted by Evelin Bakoš. Therefore we submit the following

REPORT

1 Biography

Evelin Bakoš was born on June 1, 1994, in Senta, Serbia. She enrolled in physics at the Faculty of Science in Novi Sad 2013. She graduated in 2017 with an average grade of 9.47. In 2018, she completed her master's studies in nuclear physics with an average grade of 10.00, defending her master's thesis, done in cooperation with the ATLAS group at the Institute of Physics in Belgrade, entitled *Possibilities of the ATLAS experiment for the detection of the triple production of W bosons*. The results obtained during the preparation of the master thesis are an integral part of a monograph from CERN Yellow Reports CERN-2019-007. In 2018, she enrolled in doctoral studies at the Faculty of Physics of the University of Belgrade and Radboud University in Nijmegen, the Netherlands, as a joint PhD student. She passed the scheduled exams for doctoral studies at the Faculty of Physics with an average grade of 10.00. Since October 2018, she has been elected to the position of researcher intern at the Institute of Physics in Belgrade. The topic of her research was the Search for the exclusive W boson hadronic decay of $W \to \rho\gamma$. In 2019, Evelin was engaged in performing calculation exercises for Radboud University students in the subject Standard Model (SM) and beyond. Since 2019, she has been a qualified author of the ATLAS collaboration, having completed her qualification task on the MROD-FELIX read out system integration. She presented the preliminary results of this project at the ATLAS week at CERN in 2020 in the form of a poster. During her doctoral studies, Evelin attended two international schools: the CERN Summer School in Geneva during the summer of 2018 and the BND School in Spa, Belgium, in 2019.

2 Description of submitted disertation

2.1 Basic information

The thesis was carried out under the Co-operation Agreement on Joint Doctorate between Radboud University and University of Belgrade. The supervisors of the thesis were Nicolo de Groot, professor of physics at Radboud University, and Nenad Vranješ, full research professor at Institute of Physics University of Belgrade. The subject, title and supervisors of the thesis were approved at Doctoral Collegium of Faculty of Physics Belgrade on September 29th 2021, and endorsed at the University

Council on December 13th 2021. Simultaneously the subject is approved at the Radboud University in Nijmegen.

The manuscript of the thesis has 130 pages (excluding Abstract, Table of contents, Bibliography and other auxiliary material) organised in 6 chapters, with 3 chapters containing original results (85 pages total). It has 86 figures and 25 tables. Bibliography contains 149 references. Thesis is written in English language. After running the manuscript through the software for authentication it was found that 5% of the text matches the text published elsewhere (this excludes candidates own publications). It is understood that this recognised matching is a consequence of general information mainly related to the experimental setup description and theoretical framework.

2.2 Goals and methods of the research

The doctoral dissertation incorporates three topics, all done within the framework of ATLAS experiment at the Large Hadron Collider (LHC) at CERN. The first topic covers the contribution to the data acquisition system (DAQ) of ATLAS, notably the implementation of the Muon Spectrometer Read Out (MROD) functionality to the Front-End Link eXchange (FELIX) readout system of the ATLAS detector. The second topic represents the search for the rare radiative decay of W boson to a meson and a photon, notably $W \to \rho\gamma$ decay, and it is performed by the analysis of real data collected with ATLAS during Run 2 data taking period. The third topic represents prospect study for the identification of D meson produced in a colour singlet state from radiative W decays at the LHC.

In order to maximize the possibilities of the ATLAS detector for the realization of the planned scientific program, the detector itself is going through two phases of upgrade, the first of which takes place during 2019–2022, and the second is planned for the period of 2025–2027. The expected increase in luminosity represents a significant challenge for the ATLAS detector data collection and processing system, both in terms of the amount of data and in terms of processing complexity. As part of the upgrade, a new system for reading data, Front-End Link eXchange (FELIX) is being developed. FELIX is based on FPGA technology and should replace the existing hardware system used so far in the data collection periods of the experiment (Run-1 and Run-2). The advantages of the new system are flexibility (FELIX will have less sub-detector-specific characteristics than the previous reading system), increased capacity and speed readings, software orientation and the introduction of commercial technologies earlier in the data collection chain. Processing, formatting, and data control with the FELIX system will be enabled through Software Readout Drive (`swROD`).

Partial implementation of the new system was planned and carried out before the start of the Run-3,(2022-2025(6)), and to be completed after that period, so both the old and the new system for reading run in parallel during Run-3. Specifically, in the doctoral dissertation, the candidate's task was to implement the entire functionality of the current system for reading the muon spectrometer of the ATLAS detector (MDT ReadOut Driver, MROD) in FELIX. This is a vital task for the functioning of the ATLAS detector during Run-3 since the existing MROD cards reach the end of their lifetime during the mentioned period, and their replacement is not possible. The above functionality included the incorporation of sub-detector specific data packets, specific detector settings and real-time error reporting and correction procedures, and were implemented as such in `swROD`.

The W boson predominantly decays hadronically into a quark-antiquark pair that manifests itself as a pair of jets. In rare cases, the quark pair gives rise to one or a few hadrons. Examples include decays with a meson M and a photon in the final state, of the form $W \to M\gamma$, and fully hadronic decays such as $W \to 3\pi$. These decays offer a unique opportunity to study both the weakly and strongly coupled regimes of quantum chromodynamics (QCD) in a single process. In particular, radiative decays are a test bench for the QCD factorization framework which allows the calculation of cross sections of processes at hadron colliders through the separation of perturbative and nonperturbative elements. Furthermore, these exclusive decays could be explored as a new way to measure the $W-$boson mass, which experimental precision is currently inferior to that of the prediction from the fit of SM electroweak parameters. As a result of their importance, there are multiple theoretical predictions for the branching fractions of these decays. These span orders of magnitude and experimental input is required to shed light on this puzzle.

To date, these decays have remained largely unexplored, and no exclusive hadronic decay of the W boson has been observed. A search for $W \to \rho\gamma$ has never been performed before and no upper limit on the branching fraction exists. Of all these decay modes, $W \to D_s\gamma$ has the largest branching fraction predicted by the SM, however searches have been performed by analysing specific final states $(K^+K^-\pi^+, \phi(K^+K^-)\pi, K_0^*K^+)$ which make only a fraction of all D_s decays. Stringest limit on the branching fraction is set by the LHCb corresponding to about 2×10^4 of the predicted SM value. The goals of the research conducted within the thesis were (i) to perform a search for $W \to \rho\gamma$ analysing data from pp collisions collected by ATLAS at the energy of $\sqrt{s} = 13$ TeV corresponding to integrated luminosity of about 140 fb^{-1} (ii) to perform prospects study via simulation to identify D mesons specific to radiative W boson decay using inclusive tagging, hence being sensitive to all decays at the possible expense of higher backgrounds. The traditional analysis techniques were employed for the former study, while for the later engaging and exploring machine learning techniques was necessary.

2.3 Scientific results

The candidate provided an important ATLAS service task by developing and testing software for the upgrade of the Muon Spectrometer readout system (as documented in chapter 3 of the manuscript). The test results demonstrate that the modified FELIX readout chain will be able to satisfy all requirements that come with the increased data rates in Run 3. Developed CSMswROD performs the data processing entirely on software level, which will not only be able to cope with the recommended performance, but also will ensure the system compatibility with commercial hardware. It will also open up the possibility to implement further updates and patches without switching any hardware part of the system. In addition, the system already implements new data recovery processes which was not possible with the previous MROD based read out system. The FELIX readout chain is already being utilized as the readout system of the newly installed New Small Wheels of the ATLAS detector. The FELIX-MROD project is the only ongoing effort, where the FELIX system is combined with a previously installed readout chain. This gives the project a leading role in the future FELIX readout setup for other sub-detectors and also provides an example implementation for them to follow. This is not only important for the Run 3 operation, but also for the High Luminosity-LHC upgrade. In addition, the project proves that any previous system can be adapted using FELIX cards not just in the scope of high energy physics experiments, it can be implemented in any data acquisition systems where high-speed data processing is required.

The search for $W \to \rho\gamma$ decay, described in chapter 5 of the manuscript, is performed using AT-

LAS pp collision data collected during Run 2. This search provides, for the first time, a measurement of the $W \to \rho\gamma$ branching fraction with the observed upper limit of $B < 5.17 \times 10^{-6}$ at 95% C.L. which is 592 times the predicted SM value. The analysis includes novel experimental techniques: a dedicated trigger targeting final states with a single hadron, a nonparametric background modeling method, and the unconventional use of photon triggers and τ-lepton reconstruction algorithms to target the ρ decay. In the tau-photon selection, the meson candidate is reconstructed as a hadronic τ lepton taking into account both the charged and neutral ρ meson decay products. No significant excess with respect to the background prediction is observed in the data. Upper limits are obtained using the asymptotic approximation of the profile likelihood test statistic and the modified frequentist confidence level CL_s. All systematic uncertainties are taken into account. The combined tau-photon and track-photon fit (where ρ is reconstructed via tracks) improves the observed (expected) upper limit by 18% (7%) compared to a tau-photon-only fit. The obtained results provide relevant input for the design of future collider experiments, where exclusive hadronic decays of the W boson could potentially be observed for the first time.The novel experimental techniques presented in this thesis are an initial step towards the observation of these decays in future facilities, which are currently being planned.

In order to identify D_s mesons from radiative W decays, an algorithm based on machine learning has been developed, as presented in chapter 6 of the manuscript. The study is based on a simulated paramatrised detector response in the context of ATLAS experiment and machine learning techniques to separate signal jets from quark and gluon jets backgrounds. The performance of the deep neural network and the convolutional neural network is comparable while the combined network performs slightly better: the algorithm based on a combination of deep and convolutional neural network shows a good efficiency of 47% for signal with a 100 times rejection of a background of quarks and gluons. The algorithm is stable under the variations of the simulation parameters and it also works in the presence of pile-up. The algorithm opens up the possibility to further improve measurements and searches involving D_s mesons, especially in case of the rare decays that suffer from low statistics. With low pileup dataset corresponding to the integrated luminosity of 1 fb^{-1} upper limit on branching fraction of $W \to D_s\gamma$ decay can be determined at the level of $B(W \to D_s\gamma) < 2.9 \times 10^{-4}$ which represents factor of 4 improvement with respect to the published LHCb expected upper limit.

2.4 Publications

The candidate is author of all ATLAS publications since completion of her authorship qualification task in 2020. The results presented in the submitted manuscript are published in:

- G. Aad,...,E. Bakos *et al.* [ATLAS Collaboration], "The ATLAS experiment at the CERN Large Hadron Collider: a description of the detector configuration for Run 3," JINST **19**, no.05, P05063 (2024) doi:10.1088/1748-0221/19/05/P05063 [arXiv:2305.16623 [physics.ins-det]].

- E. Bakos, N. de Groot and N. Vranjes,"Identifying D Mesons from Radiative W Decays at the Large Hadron Collider," Symmetry **15**, no.10, 1948 (2023) doi:10.3390/sym15101948 [arXiv:2207.13587 [hep-ph]].

- G. Aad,...,E. Bakos *et al.* [ATLAS Collaboration], "Search for the exclusive W boson hadronic decays $W^\pm \to \pi^\pm\gamma$, $W^\pm \to K^\pm\gamma$ and $W^\pm \to \rho^\pm\gamma$ with the ATLAS detector", accepted for publication by Physical Review Letters, [arXiv:2309.15887 [hep-ex]].

3 Conclusion

Based on the above, the general consensus of the Committee is that the work presented in the thesis *Radiative W boson decay studies and the upgrade of the ATLAS muon spectrometer readout system* submitted by Evelin Bakoš, represents original scientific achievement of the candidate, meets the international standards in the field of experimental high energy physics and within the ATLAS experiment community in regard to quality, reproducibility and research data management. Thus, the final verdict is to recommend its public defence.

Belgrade and Nijmegen,
September 5th, 2024

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