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Prof. dr Predrag Miranović

Poštovani profesore Miranoviću,

U prilogu ovog akta dostavljamo Vam doktorsku disertaciju mr **Jelene Mijušković** pod naslovom **"Mjerenje N – džetnosti varijabli u događajima sa produkcijom Z bozona u CMS detektoru i performanse njegovog elektromagnetnog kalorimetra"** i Izvještaj o ocjeni doktorske disertacije koji su u skladu sa članom 42 stav 3 Pravila doktorskih studija dostavljeni **Centralnoj univerzitetskoj biblioteci** 30. 03. 2022. godine, na uvid i ocjenu javnosti.

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mr Bosiljka Cicmil

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Council of the Faculty of Science and Mathematics

Senate of the University of Montenegro

Referee's report of the PhD thesis

" Measurement of the N-jettiness variables in the production of Z boson events with the CMS detector and performance of its electromagnetic calorimeter "

written by PhD student Jelena Mijušković

The undersigned dr Ulla Blumenschein, senior lecturer at School of Physics and Astronomy, Queen Mary University of London, dr Marco Delmastro, research director at LAPP, Univerzitet Savoie Mont Blanc, LAPP, CNRS/IN2P3, Annecy, France, Dr Federico Ferri, researcher with habilitation (habilitation à diriger des recherches) at CEA- IRFU, Saclay, Paris, Dr Philippe Gras researcher with permanent position at CEA- IRFU, Saclay, Paris and Dr Nataša Raičević, professor at University of Montenegro, nominated with the Decision No. XXX from YYYY of the Senate of the University of Montenegro as members of the Committee for review and evaluation of the doctoral dissertation "Measurement of the N-jettiness variables in the production of Z boson events with the CMS detector and performance of its electromagnetic calorimeter " elaborated by the doctoral student Jelena Mijušković, present the following referee report.

The scientific area of the thesis is Elementary Particle Physics also called High Energy Physics. This thesis presents the measurements of the differential cross section of Z boson production in association with jets in proton-proton collisions at center of mass energy of 13 TeV. The analysed data has been collected by the CMS (Central Muon solenoid) experiment of LHC (Large Hadron Collider) during the year 2018 and corresponds to an integrated luminosity of 59 fb^{-1}. The main focus of the thesis is the measurement of N-jettiness variables, τ_N:

$$\tau_N = \sum_k \min\{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k \ldots q_N \cdot p_k\}$$

where p_k is the four-momentum of particle k, q_a and q_b are the four-momenta of the beams and $q_1,\ldots,q_N$ represents the four-momenta of N jets in the event. For events with at least N jets, in the limit when $\tau_N \to 0$, the event contains N narrow jets.

In this thesis, the cross section is measured as a function of track-based event shape variables: zero-jettiness (τ_0), one-jettiness (τ_1) and the sum of the transverse momentum of particles.

Beside the track based variables, the so called jet based variables are also measured. These variables use jets reconstructed with the anti-k_T algorithm. Jet based variables, are defined via:

$$\tau_j = p_T^j \frac{1}{2\cosh(y_j - Y)},$$

where p_T^j and y_j are transversal momentum and rapidity of jet j and Y is Z boson rapidity. The cross section measurements depending on $\tau_{max} = \max_j \tau_j$ and $\tau_{sum} = \sum_j \tau_j$ are presented.

The measurements of event shape variables are performed for the events where pairs of muons are produced in the decay of a Z boson on-shell with an invariant mass between 76 and 106 GeV and also for off-shell Z bosons with an invariant mass between 125 and 150 GeV, 150 to 350 GeV and 350 and 1500 GeV and in four different Z boson transverse momentum regions.

The measurements have been compared with two theoretical predictions based on fixed-order parton-level cross sections calculated at LO or NLO accuracy in QCD for different ligh-parton multiplicities, merged and matched with parton shower. They have been computed with MadGraph5_aMC@NLO. The former merges multiplicities from zero to four at LO, and the latter from zero to two at NLO. The measurements are also compared with a predication at NNLO at fixed order combined with the resummation of higher-order terms in 0-jettiness and matched with parton shower obtained with the Geneva event generator.

Part of the thesis is devoted to the studies of the performance and the calibration of the Electromagnetic calorimeter (ECAL) of CMS during the Run 2 data taking period (2016, 2017 and 2018 years). This subdetector is crucial for the detection of photons, electrons and positrons and is therefore very important for many analyses in CMS.

This thesis consists of an introductory part, five chapters and a conclusion. The list of figures and tables are provided. The dissertation is preceded by an abstract written in Montenegrin, French and English. The theoretical introduction to the Standard Model is described in chapter 1. In chapter 2, the CMS detector is presented. Intercalibration and performance of ECAL is described in chapter 3. The measurements of track-based event shape variables are presented in chapter 4, and the measurements of jet-based event shape variables are presented in chapter 5. Summary and conclusions follows.

Chapter 1 describes the theoretical basis of the Standard Model. The theories and Lagrangians that describe fundamental interactions are briefly summarized: quantum electrodynamics, quantum chromodynamics and electroweak theory with electroweak symmetry breaking. Main concepts Beyond the Standard Model theory are discussed and conclude section 1.1 of this chapter. The theoretical treatment of the computation of the cross-section of proton-proton interactions, with collinear factorisation and Parton Density Functions are descried in section 1.2. After this general part, in section 1.3 Drell-Yan processes are explained in detail. The main diagrams, LO and NLO associated to them are discussed as well as higher order diagrams which include loops of quarks and gluons. With these additional terms the logarithms of the form $(\alpha_s \log Q^2/M^2)^n$ where n is the number of quark (gluon) loops and M the renormalization point of the strong coupling, α_s , are introduced. Also, additional radiation that can occur by quarks and leptons is explained.

The section 1.4 introduces Monte Carlo (MC) simulations which include physics processes and also the response of the detectors and have very important role for measurements and new discoveries. The main concepts of generators used in the comparison of data and theoretical predictions, MadGraph5_aMCc@NLO and Geneva are described.

Chapter 2 describes the experimental setup. Protons are accelerated in the Large Hadron Collider (LHC) and the particles produced in their collisions are detected with the CMS detector. CMS is a very sophisticated apparatus made of subdetectors using different technologies. By combining the information from the subdetectors, the complete kinematics of each collision is reconstructed: the produced particles are identified and their momenta and energies are measured. In this chapter, the accelerator system and the detector with its subsystems are presented. In section 2.1 a brief description of LHC, its design, performance, operation and future plans are given. Section 2.2 is devoted to the CMS experiment. The CMS coordinate system and the main the kinematic variables that describe particles created in proton-proton interactions are defined. The design and performance of the key components of CMS are briefly described: the superconducting solenoid, the tracker, the electromagnetic and hadronic calorimeters as well as the muon system. After this, the concept and logic of the trigger system is explained. The reconstruction of particles inside the detector is described in section 2.3. It explains track and vertex reconstruction, electron and photon reconstruction, muon reconstruction as well as the particle flow algorithm based on information from different detector systems. This chapter is concluded by section 2.4 in which the CMS upgrade for the phase of high luminosity (HL) is described.

As mentioned above, a part of the thesis is devoted to intercalibration and performance studies of the CMS electromagnetic calorimeter, which is described in **Chapter 3**. The excellent resolution of the CMS electromagnetic calorimeter plays an important role in many physics analyses performed at CMS. In particular, its precise measurement of the electron and photon energy had an essential contribution in the discovery of the Higgs boson through the $H \rightarrow \gamma\gamma$ channel during the LHC Run 1 period. In order to optimize the performance, a calibration of the relative response of the ECAL channels and corrections for the response variation in time are performed. The Run 2 data taking period, with the increased pileup and radiation level, created a challenging environment for ECAL.

The energy and signal reconstructions in the ECAL are described in sections 3.1 and 3.2. Since the response of the ECAL varies with time due to the crystal transparency variation induced by irradiation, constant calibration of the detector is performed. The laser monitoring system used for monitoring the crystal transparency is described in Section 3.3. A part of this PhD work was devoted to the intercalibration of the ECAL using the Drell-Yan process where electron-positron pairs are produced. The intercalibration constants were obtained for all three years of the Run 2 period. In addition, this thesis includes work on resolution studies for the Run 2 period and a comparison of the performance of ECAL during Run 1 and Run 2. In section 3.4 the different intercalibration methods are described while section 3.5 provides more detail on the one exploiting the Drell-Yan processes. The plans for the ECAL barrel readout electronics for the HL-LHC are described in Section 3.6.

In **Chapter 4**, the measurements of the differential cross section for the production of a Z boson as a function of track based event shape variables, τ_0 and τ_1, and as function of the sum of the transverse momentum of charged particles are presented. The Z bosons are selected by their decay channel into two muons. The measurement is done for both on- and off- shell bosons and includes also the contribution from γ^*. The event shape variables are computed with charged particles only in order to constrain the contributions coming from the pileup particles. The measurements are performed in four different transverse momentum, p_T (Z), regions and in three different dilepton mass (M_{ll}) regions. In the first part of this chapter (Section 4.1), the measured variables are defined. In Section 4.2, data samples and simulated samples are presented. The selection criteria for the events and for the particles used for the N-jettiness calculation are described in Section 4.3. The event selection is based on the identification of two muons with high quality tracks combined from the tracker and muon systems. Beside the track quality these muons are required to be well isolated from jets to exclude muons produced in hadron decays. In addition, it is required that one of the two muons has a transverse momentum above 25 GeV and the other above 20 GeV. Charged particles selected for the calculation of track-based variables are required to have a minimum transverse momentum of 1 GeV. Only particles within the tracker pseudorapidity full-precision acceptance, $|\eta| < 2.4$, are considered. The main challenge for these measurements is the presence in the recorded events of many overlaping proton-proton collisions, 35 on average, called pileup and occurring at the same time as the collision producing the Z boson because of the high luminosity of the colliding beams. To suppress the contribution from pileup, the selected particles are required to issue from the primary vertex of the interaction of interest.

The response of the detector is simulated in detail with a sophisticated software modeling the interaction of each particle with its material and emulating the readout electronics. The simulation is compared with the real data to measure any difference. The Section 4.4 describes the extraction of corrections which are then applied to further improve the accuracy of the simulation. These corrections are common to all the analyses performed with the CMS data. The calculation of the trigger scale factor was part of the thesis work and has been done using the *Tag-and-Probe* method, while the other corrections were computed by some other CMS collaborators. After the corrections were applied, the detector distributions of muon and muon pairs were compared with the simulation. The comparison was also done for the track variables. In order to compare the obtained results with the theoretical predictions or with the results from other experiments, the measurements have to be corrected for the detector effects such as object reconstruction, inefficiency inside the acceptance of the detector and the misidentification of the objects of interest. In addition, since the reconstruction system has a finite resolution, the measured value of an observable usually does not correspond to the true one. The techniques for the deconvolution of the detector effects are presented in Section 4.5. In section 4.6, the following systematic uncertainties were explained and calculated: pileup, luminosity, background, lepton energy scale, lepton energy resolution, lepton reconstruction and trigger efficiency, track momentum, track efficiency and unfolding method. This section also includes a detailed explanation of the theoretical prediction uncertainties. The measurements of track-based variables are shown in section 4.7. The measurements are performed for events with a Z boson with invariant mass between 76 and 106 GeV, corresponding to the peak region, 125 and 150 GeV, 150 and 350 GeV and 350 and 1500 GeV. Track-based variables are also measured in four

different Z boson transverse momentum regions: bellow 6 GeV, from 6 to 12 GeV, from 12 to 25 GeV and above 25 GeV. For all the cases, the detector level distributions are also shown. The measurements have been compared with the three theoretical predictions described in the introduction.

Chapter 5 contains the results of measurements of jet based event shape observables in the production of the Z boson in association with jets. These observables are measured in events with a Z boson in the mass peak region. The definitions of the jet based observables, τ_{max} and τ_{sum}, are presented in Section 5.1. The importance of the cross section measurement dependence on such variables and their advantages with respect to the jets selection according to their transverse momentum value is explained. Section 5.2 describes jet reconstruction and selection. Two methods of suppression of the pileup contribution from the jet reconstruction are compared and the one more appropriate for the N-jettiness measurements is adopted. Section 5.3 explains additional systematic uncertainties which arise due to the jet selection: the jet energy scale and jet energy resolution uncertainties. The results are presented in section 5.4 starting with results on all the uncertainties of the jet based variables. The detector level distributions comparison between data and Monte Carlo are shown. The results on the differential cross sections on jet based variables conclude this chapter. The experimental measurements are compared with the same theory calculations as used in chapter 4.

Finally, the results of the thesis are summarized in the **Conclusion**.

Conclusions

Differential cross sections have been measured as a function of track-based event shape variables and as a function of jet-based event shape variables. The measurements have been compared with two theoretical predictions based on fixed-order parton-level cross sections calculated at LO or NLO accuracy in QCD for different ligh-parton multiplicities, merged and matched with parton shower computed with MadGraph5_aMC@NLO, one merging multiplicities from zero to four at LO and the other from zero to two at NLO. They have also been compared with a predication at NNLO at fixed order combined with the resummation of higher-order terms in 0-jettiness and matched with parton shower obtained with GENEVA. Track-based variables that have been measured are the zero-jettiness, one-jettiness and the sum of the transverse momentum of charged particles. These variables can be used as a veto for hard radiation or jets and to define a theoretically well-controlled exclusive N-jet cross section. Track based variables are very sensitive to the underlying events and soft radiation, therefore studies of these variables give valuable input for event generator developments. The measurements are performed for the events with pairs of muons produced in the decay of an on-shell Z boson with invariant mass between 76 and 106 GeV, and for the off-shell Z boson with invariant mass between 125 and 150 GeV, 150 and 350 GeV and 350 and 1500 GeV. Track based variables are also measured in four different Z boson transverse momentum regions. The measurements for on-shell Z bosons showed that the low zero-jettiness region in the inclusive case is best described by the GENEVA prediction. In the higher Z boson transverse momentum region, where we expect to have one or more jets accompanying the Z boson, among the predictions MADGRAPH5 aMC@NLO is

doing best. For the higher invariant mass regions, all predictions show a fair agreement with the data. Measurements of these variables show a good potential for studies of the underlying events. By studying track based variables for the invariant mass above the Z peak, the regime similar to the Higgs boson has been explored. Jet-based variables that have been measured are τ_{max} and τ_{sum}. These variables are defined using the jet transverse momentum weighted by a rapidity dependent function. Jet-based variables introduce a possibility to apply a tight veto on central jets while at forward rapidities the veto constrain gets looser. The τ_{max} variable showed a good agreement with the predictions, especially with MadGraph5_aMC@NLO. This variable can be used as a jet veto.

Opinion and proposal of the commision

The thesis presents the first measurements of the N-jettiness variables in the production of real and virtual Z boson events with the CMS detector and performance of its electromagnetic calorimeter.

Because of the good convergence of its cross section perturbative series, the production of a Z boson is an excellent playground to test resummation and confront the calculations with measurements. Resummation regimes similar to the Higgs boson can be reached requiring an off-shell Z boson with a high Z mass.

The electromagnetic calorimeter plays a crucial role within the CMS detector system and such good resolution achieved with the contribution of the work presented in this thesis is of vital interest for the scientific program of the collaboration.

Results of the dissertation have been shown at international conferences and CMS workshops. The results on the electromagnetic calorimeter have been published in the Journal of Instrumentation which is a leading journal in particle physics instrumentation.

Jelena Mijušković on behalf of the CMS collaboartion
„The CMS electromagnetic calorimeter upgrade: high-rate readout with precise time and energy resolution“,
Journal of Instrumentation (JINST) 2022 17 C01004

A publication of the measurements of the N-jettiness variables is in preparation. The analysis and the paper draft are currently under review within the CMS collaboration.

Having in mind all the above, the commission is pleased to propose to the Council of the Faculty of Natural Sciences and Mathematics of the University of Montenegro to accept the doctoral dissertation entitled “Measurement of the N-jettiness variables in the production of Z boson events with the CMS detector and performance of its electromagnetic calorimeter” of candidate Jelena Mijušković, as well as to propose to the Senate of the University of Montenegro, to appoint a commission for the defense of this doctoral dissertation.

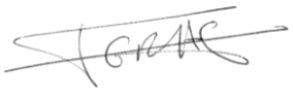
28.3.2022.

Committee for review and evaluation of the doctoral dissertation

Dr Ulla Blumenschein

Dr Marco Delmastro

Dr Philippe Gras



Dr Federico Ferri

Dr Nataša Raičević

Na osnovu člana 32 stav 1 tačka 14 Statuta Univerziteta Crne Gore, u vezi sa članom 41 Pravila doktorskih studija, Senat Univerziteta Crne Gore, u postupku razmatranja predloga Vijeća Prirodno-matematičkog fakulteta i utvrđivanja ispunjenosti uslova iz Pravila doktorskih studija za ocjenu doktorske disertacije i dalji rad na disertaciji mr Jelene Mijušković, na predlog Odbora za doktorske studije, na sjednici održanoj 09.03.2022. godine, donio je sljedeću

O D L U K U

I

Utvrđuje se da su ispunjeni uslovi iz člana 38 Pravila doktorskih studija za ocjenu doktorske teze i dalji rad na disertaciji „Mjerenje N-džetnosti varijabli u događajima sa produkcijom Z bozona u CMS detektoru i performanse njegovog elektromagnetnog kalorimetra" kandidatkinje mr Jelene Mijušković.

II

Imenuje se Komisija za ocjenu navedene doktorske disertacije, u sastavu:

1. Dr Nataša Raičević, redovni profesor Prirodno-matematičkog fakulteta Univerziteta Crne Gore,
2. Dr Federiko Ferri, istraživač Instituta CEA-IRFU, Saclay, Pariz
3. Dr Marco Delmastro, istraživač Univerziteta Savoie Mont Blanc, Annecy, Francuska
4. Dr Ula Blumenschein, senior predavač u Školi fizike i astronomije, Queen Mary Univerziteta London, Velika Britanija
5. Dr Philippe Gras, istraživač Instituta CEA-IRFU, Saclay, Pariz

III

Zadatak Komisije je da, u roku od 60 dana od dana dostavljanja odluke podnese Vijeću Prirodno-matematičkog fakulteta i Senatu izvještaj o ocjeni navedene doktorske disertacije.

IV

Odluka stupa na snagu danom donošenja.

Broj: 03- 222/1
Podgorica, 09.03.2022. godine

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PREDSJEDNIK SENATA

Prof. dr Vladimir Božović, rector