OCJENA PODOBNOSTI DOKTORSKE TEZE I KANDIDATA

OPŠTI PODACI O DOKTORANDU	
Titula, ime i prezime	Mr Itana Bubanja
Fakultet	Prirodno - matematički fakultet
Studijski program	Fizika
Broj indeksa	1/2020
Podaci o magistarskom radu	„Analiza dileptonskih parova iz raspada Z bozona nastalih u proton-proton interakcijama na energiji od 5 TeV na CMS eksperimentu“, Eksperimentalna fizika čestica, Prirodno-matematički fakultet, Univerzitet Crne Gore, 23.9. 2019, A (9.92).
NASLOV PREDLOŽENE TEME	
Na službenom jeziku	Produkcija naelektrisanih leptonskih parova kroz Drel-Jan proces u proton-proton sudarima na LHC-u
Na engleskom jeziku	Production of charged lepton pairs through the Drell-Yan process in proton-proton collisions at the LHC
Datum prihvatanja teme i kandidata na sjednici Vijeća organizacione jedinice	24.12.2021.
Naučna oblast doktorske disertacije	Eksperimentalna fizika elementarnih čestica
Za navedenu oblast matični su sljedeći fakulteti	
Prirodno-matematički fakultet, Univerzitet Crne Gore	

A. IZVJEŠTAJ SA JAVNE ODBRANE POLAZNIH ISTRAŽIVANJA DOKTORSKE DISERTACIJE

The defense of the initial research of the doctoral student Itana Bubanja, M.Sc., was realized on March 16th, 2022 starting at 11:00 am. The Defense Commission was composed of:

1. Dr Slobodan Backović
2. Dr Ivana Pićurić
3. Dr Hannes Jung
4. Dr Laurent Favart
5. Dr Nataša Raičević

The defense (presentation of the doctoral student's initial research, questions and discussion) ended at 12:00.

During the defense, the doctoral student presented the motivation of the research and a short overview of ongoing publication from the CMS collaboration focused on the emission of Drell Yan lepton pairs in proton-proton collisions.

The candidate explained in detail the work she has performed so far which can be briefly summarized in the following:

1. The first results on detector level distributions of lepton pair transverse momentum for different pair invariant mass bins of Drell-Yan analysis of 2017 data. Data are compared with the full detector simulation of events obtained using Madgraph event generator. Also, background contribution was completely simulated. The analysis was done using SHEARS framework (The Simple and Handy Event Analysis ROOT-based Suite).

2. First analysis of the Z boson production for 13 TeV data from 2016 using new data format called NanoAOD. This is Ntuple like format - readable with bare root, per-event information needed for analysis, the size per event - order of 1Kb which presents the significant reduction to the previously used formats. The distributions on azimuthal opening angle between the lepton tracks ($\Delta\Phi$) was also shown and its correlation to the pair transverse momentum was discussed.

3. The Rivet routine (Robust Independent Validation of Experiment and Theory) is used for validation of Monte Carlo event generators. It is one of the important steps in the approval of the papers in CMS. In order to be sure that Rivet routine is in agreement with the analysis code performed for obtaining results of Drell Yan lepton pairs which will be published soon by CMS, several validation steps were performed. Also, the results from Rivet 2 and Analysis code were compared. Rivet 3 validation was done by comparing it with Rivet 2 results.

4. The comparison of different tunes used in CMS collaboration for simulation of underlying event and multi-parton interactions. The tunes were also compared with experimental measurements of pair transverse momenta.

After the defense, all members of the Commission asked questions, commented on the results so far and suggested further work on the dissertation. The Commission noted that this is a challenging and demanding topic that would include the measurement of differential cross-sections for the production of Drell-Yan with the highest precision to date at the LHC. The commission also noted that the results of the candidates' work so far are at the rather high level.

B. OCJENA PODOBNOSTI TEME DOKTORSKE DISERTACIJE

B1. Obrazloženje teme

The work of the thesis is in the field of particle physics i.e. high energy physics. The production of charged lepton pairs through the Drell-Yan (DY) process from proton-proton (pp) collisions at a center of mass energy of 13 TeV is analysed. The focus is on transverse momentum distributions of the pairs. Transverse momentum is momentum projection on the plane perpendicular to the beamline. Protons with equal energies which collide head-on are accelerated at the Large Hadron Collider (LHC) – the world's largest collider situated at CERN in Geneva. The experimental data to be analysed are obtained by the experimental apparatus of Compact Muon Solenoid (CMS) – a complex multi-purpose detector system.
Protons are not pointlike particles but have many constituents: electrically charged quarks and antiquarks and neutral gluons (quarks and antiquarks are particles with fractional electric charge, $\pm 2/3e$ or $\pm 1/3e$, with e being electron charge). The gluons inside the proton hold the charged partons together via the strong force and the (anti)quarks interact themselves by exchanging gluons which are mediators of the strong force, described in detail within quantum chromodynamics (QCD) theory. Together, all constituents of the proton are called partons. The high-energy collision of protons is actually the collision of partons they are made of.
In the collision, a quark and an antiquark from the interacting protons can annihilate and create

a boson. If their net charge and total flavor are zero, a virtual photon (γ*) or Z boson is created and if this is not a case a W boson is created. The γ* or Z boson decaying in a charge lepton and its antiparticle (l^+l^-) is called the Drell-Yan (DY) process. Such a lepton pair is produced after brief propagation of created neutral boson, γ*/Z, after which it splits to an l^+l^- pair. Since in this process momentum has to be conserved, the momenta of l^+ and l^- add up to the momentum of γ*/Z boson. If the lepton pair is created via virtual photon then it corresponds to an electromagnetic process while if it is created from the Z boson the process which occurs via the weak interaction has taken place. The invariant mass of the lepton pair corresponds to the mass of the γ*/Z. For masses well below the rest energy of Z, the electromagnetic process is the dominant one while at masses around this value, the dominant mechanism is the creation of DY via the weak interaction. In this work, the creation of electron pairs (e^-e^+) and muon pairs ($\mu^-\mu^+$) will be analysed.

However, the DY mechanism, in reality, is not as simple as explained above. Real collisions also include the underlying events (UE) which consist of the beam-beam remnants (BBR) and particles that arise from multiple-parton interactions (MPI). The BBR is what is left after a parton is knocked out of each of the two initial proton beams. The MPI are additional soft or semi-hard parton-parton interactions that occur within the same pp collision.

Before their annihilation, quark-antiquark pairs that participate in the DY process can radiate gluons. Also, the interacting quark and antiquark from the protons can come not directly from the protons but produced by gluons of the protons. So, together with the dilepton pair (coming from a neutral boson which is created from one quark and one antiquark) there can be emission of additional partons. According to the QCD, through the process called hadronisation such partons materialize into several hadrons that are emitted within a narrow cone whose axis is along the direction of the initial parton. Such structures in high-energy physics are called hadronic jets. Although less common, from time to time energetic jets (created from quarks and gluons) will be emitted alongside a neutral boson. Since the cross section, which is a measure of the process production rate, decreases with additional emissions (because of a small value of the strong coupling constant at high energy), producing a boson with more energetic jets is less likely than having fewer jets. Concerning the low energy jets (soft jets), the situation is different. DY pairs are easily accompanied by soft jets.

To gain in statistics, nowadays accelerators operate in the condition of high luminosity which provides a huge number of interactions per second and the experiments deal with the problem that the interaction i.e. the hard process of interest cannot be completely separated. At the LHC the protons are accelerated in so-called bunches and each bunch consists of more than a billion of protons. The proton-proton collisions occur in the two bunch crossing. There are about 20 interactions per bunch crossing i.e. within 25 ns. 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 dilepton pairs because of the high luminosity of the colliding beams. Since particles and jets emitted from pile-up are rather soft, their contribution is reduced by defining cuts on the energy of the detected objects to be considered. Hence, experiments are insensitive to very low energy products, and not everything from a pp collision will be recorded.

Soft gluons, even if they cannot be individually reconstructed, still affect the process. Because the gluons carry away energy, due to momentum conservation the system will be slightly pushed and somewhat kicked in different directions. Therefore by measuring the momentum of the emitted γ*/Z boson we can get information about soft processes even if undetected and identified them experimentally.

The perturbation theory is the tool used to calculate the probability of some process happening during a pp collision. It assumes that the emitted objects (particles and jets) have much higher energy than the proton at rest and is therefore not applicable to the situation where we have an emission of soft gluons. Therefore, for this low-energy part, the modeling of the soft processes has to be done and compared with experimental results.

B2. Cilj i hipoteze

Cilj rada

The main goal of the thesis is to obtain DY differential cross section measurements as a function of the transverse momentum and azimuthal angle opening between pair leptons in a wide range of pair invariant mass using complete statistics of data collected by CMS during the whole Run II period of LHC running. Therefore, this is expected to be the highest precision measurement of the DY differential cross sections obtained so far in CMS collaboration.

The measurements to be obtained in this thesis are the following:

1. Detector distributions for all relevant variables of the DY pairs for both dielectron and dimuon channels: lepton momentum, lepton rapidity, pair invariant mass, pair rapidity, transverse momentum of the pairs (p_T), azimuthal angle opening between pair leptons ($\Delta\Phi$).
2. Comparison of the above detector distributions obtained from data and the full Monte Carlo (MC) simulation. The MC simulation includes a detailed simulation of all CMS detector component responses including simulation from physics contribution of lepton pairs and all significant sources of background from pp collisions.
3. Measurement of inclusive differential cross sections in dilepton transverse momentum in different invariant mass intervals.
4. Ratios of inclusive differential cross section in dilepton momentum in different invariant mass intervals and the inclusive differential cross section in the Z peak region for each year and the combined ones.
5. Measurement of inclusive differential DY cross section in $\Delta\Phi$ in different invariant mass intervals.
6. Ratios of inclusive DY differential cross section in variable $\Delta\Phi$ in different invariant mass intervals and the inclusive differential cross section in the Z peak region.
7. Measurement of inclusive one energetic jet differential cross sections in dilepton transverse momentum in different invariant mass intervals.
8. Ratios of inclusive one energetic jet differential cross section in lepton pair momentum in different invariant mass intervals and the inclusive differential cross section in the Z peak region for each year and the combined ones.
9. Comparison of the above measurements with most recent theoretical predictions including different scenarios in QCD and the soft gluon resummation.
10. Comparison of the above measurements with theoretical predictions including different tunings for underlying events available at CMS.

Hypothesis 1: The detector distributions for the dilepton pairs are well reproduced by the full Monte Carlo simulation.

Hypothesis 2: The DY differential cross section measurements and the corresponding ratios are reproduced by theoretical models which include QCD and different scenarios of soft gluon resummation.

Hypothesis 3: The DY differential cross sections and the corresponding ratios depend on the set of CMS tunes of underlying events.

B3. Metode i plan istraživanja

Material

The experimental material used in this thesis is obtained by using CMS detector at CERN in Geneva from 2016 to 2018 (Run II period of data collection from LHC).
For the simulation of DY signal created through the Z/γ^* process, including also the $\tau^+\tau^-$ background, MADGRAPH5 at NLO, AMC@NLO. The parton shower, hadronisation, and QED final state radiation will be performed with PYTHIA8.
Experimentally reconstructed lepton pairs are not coming only from DY process but will contain pairs from other processes - background processes.
Several physical and instrumental backgrounds contribute. The main backgrounds in the region of high invariant masses (above the Z peak) are due to $t\bar{t}$ and diboson production followed by leptonic decays, while the DY production of $\tau^+\tau^-$ pairs is the dominant source of background in the region just below the Z peak. At low values of the dimuon invariant mass (up to 40 GeV), most of the background events are due to QCD events with multiple jets. The situation is slightly different for electrons in the final state. At low values of dielectron invariant mass, most of the background events are from $\tau^+\tau^-$ and $t\bar{t}$ processes, whereas the contribution from the QCD multijet process is small due to the tighter selection for electrons compared to muons. The pairs from such background processes have to be estimated and subtracted from the measured sample.
For each set of the MC samples, the detector response on particle passage through it is simulated using a detailed description of the CMS detector material and acceptance based on the GEANT4 package. The simulated events are reconstructed using the same software as the real data.

Methods

CMS detector has a compact structure with many subdetectors systems. The central part of CMS detector is a large superconducting solenoid with a length of 12.5 m and a radius of 6 m. The value of the magnetic field that can be produced using this solenoid is 4T. The tracking detector, the electromagnetic calorimeter (ECAL), and the hadron calorimeter (HCAL) are all installed inside the solenoid. Outside the solenoid, the iron return yoke of the magnet is placed, interleaved with layers of muon detector.
Particle Flow algorithm (PF) is used by CMS collaboration for reconstruction and identification of particles. PF combines the information of all the CMS subdetectors. It ensures the best possible identification and energy measurements for all types of objects. From tracker and muon system information about tracks of particles are taken and from the ECAL and HCAL, the position, energy and time of arrival of particles can be determined. PF algorithm is used for the identification and reconstruction of electrons, muons, photons, neutral and charged hadrons. It also plays role in jet reconstruction and missing transverse momentum determination. The reconstruction process of some of the particles used in this analysis can be described shortly as follows:

- Electrons and photons – They deposit all their energy only in the ECAL. As they propagate through the material of the detector they interact with the material. As a result of these interactions, they may no longer be detected as a single particle but they can form a shower of multiple electrons and photons. The energy deposits these particles leave in the ECAL are called super-clusters. In addition, electrons leave hits in the tracker layers.
- Charged and neutral hadrons – These particles are identified inside the HCAL and ECAL. Although they initiate a shower in ECAL, it is fully absorbed in the HCAL. Charged hadrons leave hits inside the tracker and corresponding clusters in the HCAL are used to determine their position and energy. Neutral hadrons are identified as energy deposits in the ECAL and HCAL that cannot be matched with hits in the tracker. For each event, hadronic jets are clustered from these reconstructed particles using the anti-k_T algorithm with a distance parameter of 0.4. Jet momentum is determined as the vector sum of all particle momenta in the jet.
- Muons – They ionize the gas in the muon chambers, thus the electric signal is produced on wires and strips. This signal together with the signal obtained from the tracker is used for the determination of muon properties.

The position along the beam axis where the pp interaction happens is called a vertex. For high pile-up, many vertices belong to the main event, but one is called a primary vertex. The candidate vertex with the largest value of summed physics-object transverse momenta squared is taken to be the primary vertex of pp interaction. The physics objects are the jets, reconstructed using the jet-finding algorithm with the tracks (also including electrons and muons) assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the transverse momenta of those jets.
Events of interest are selected using a two-tiered trigger system. The first level trigger, consisting of hardware processors, uses signals from the calorimeters and muon detectors to select events. The rate of the L1 is at around 100 kHz within a fixed latency of about 4 μs. The second level trigger, known as the high-level trigger (HLT), contains information from a farm of processors running a version of the full event reconstruction software optimized for fast processing. HLT reduces the event rate to around 1 kHz before data storage.

In this analysis, the event selection proceeds via several steps:
- The two most energetic lepton candidates of the same flavor, but different electric charge signs are selected. The cuts on the lepton transverse momenta depend on available triggers. The leptons are required to be well reconstructed i.e. identified and isolated and to achieve this, additional cuts are applied;
- The lepton candidate must be emitted within the detector acceptance so the lepton pseudorapidity is limited to $|\eta| < 2.4$;
- Tracks not belonging to the primary vertex are identified as pile-up contribution and are not considered for jet energy and momentum;
- The two selected leptons are not taken into account in the jet collection if they are enough separated from it. A separation $\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$ is measured with $\Delta\eta$ and $\Delta\varphi$ being differences in pseudorapidity and azimuthal angle between lepton candidate and jet directions. ΔR between the reconstructed jets and the lepton candidates is required to be larger than 0.4;
- The pile-up contamination is further reduced by requiring the jet to have a minimum transverse momentum and good quality of the track reconstruction. Selected jet has to be

in a rapidity range of $|y| \leq 2.4$.

Monte Carlo simulation of the detector responses, resolution, and efficiencies has to be as close as possible to the experimental situation which also means that the efficiencies of the applied cuts have to be reproduced. To achieve this, the additional scale factors will be applied to Monte Carlo simulated events.
The overall detector resolution and efficiency will be corrected by the unfolding procedure.
Reconstruction of simulated events will be done in the same way as for the experimental data. In order to analyse both experimental and simulated data, the programming languages C++ and Python in CMS software environment will be used. The analysed distributions will be plotted in ROOT which is a widely used software package in particle physics.

Research plan

To obtain each of the above-listed cross section measurements, a common set of steps will be performed. The steps are the following:

- Event selection;
- Efficiency corrections implementation;
- Backgrounds estimation;
- Background subtraction;
- Yield unfolding;
- Correction for the effects of the migration of events among different bins of measured variables due to the detector resolution;
- Application of the acceptance and efficiency corrections;
- Correction of the migration of events due to final state radiation;
- Evaluation of systematic uncertainties associated with each of the analysis steps.

B4. Naučni doprinos

Since the DY production of lepton pairs in hadronic collisions proceeds as a result of the collision of hadron constituents (partons), the expected high precision measurement will provide very important insights into the internal structure of hadron as well as the parton evolution.
The lowest order or the leading order (LO) DY production is described as a so-called s-channel exchange of Z and γ^* bosons. In such a process, a quark from one proton and an antiquark from another proton annihilate to a neutral vector boson by the electroweak process. The Z/γ^* exchange factorises to collinear quark and antiquark proton parton distribution functions (PDF). In this case, the DY pair transverse momentum is equal to zero. If there is initial state radiation (ISR) then we are dealing with higher-order processes. This ISR is QCD radiation since it is connected with radiation of gluons from incoming partons which gives rise to sizable DY pair p_T. The contribution of an additional emission contains multiplication with the coupling constant which is sizable for low energy or soft processes. Hence, the region of large pair p_T which is the result of hard QCD radiation is expected to be described with fixed-order calculation in perturbative QCD (pQCD) due to the small value of running strong coupling constant while the region of small pair p_T requires the soft gluon resummation to all orders. Also, the small p_T region includes the effect of internal transverse motion of the partons inside of the colliding protons which should be extracted from data and modeled using parameterizations. Hence, the pair p_T measurements provide a test of the validity of the general approach and the precision of the different model predictions. Inclusive DY production calculations can be performed as a function of pair invariant mass and pair p_T and are available up to next-to-leading-order (NLO)

in the electroweak coupling and up to next-to-next-to-leading-order (NNLO) in pQCD. Therefore, a precision measurement of the DY mass and p_T differential cross sections at the LHC provides an important test and input for the perturbative framework of the Standard model. In a complementary way, the experimental measurements can also be used to constrain the PDFs.
The leptons from the final state pair can radiate photons (radiation of Quantum Electrodynamics – QED) which will certainly affect the DY p_T spectrum. This radiation is called QED final state radiation. Such radiation will also have an impact on pair mass distribution, especially for masses below Z boson mass where migrations from the Z peak can be significant. MC simulations that perform parton showering, such as Pythia8, include QED radiation from Z boson decay at leading order which could be confirmed with high statistics sample of Z bosons recorded at LHC. This study is also important to evaluate the NLO electroweak corrections available in MadGraph5_aMC@NLO.
High statistics of DY production of dileptons is also a major source of background for rare processes from the Standard Model as well as searches for physics beyond the Standard Model. Therefore, it is important to measure the DY production rate accurately up to the largest accessible energy.

B5. Finansijska i organizaciona izvodljivost istraživanja

Itana Bubanja, MSc, works on a joint doctorate from the University of Montenegro and the Free University of Brussels - ULB (Université libre de Bruxelles) in Brussels, Belgium. The plan is that the doctoral student spends about half of her research time on the doctoral thesis at each of the universities with occasional stays at CERN. Due to the covid pandemic, the doctoral student is currently working at the University of Montenegro, and at the Faculty of Science she is employed as a research associate and is funded by a project supported by the EU program HORIZON 2020 (*The strong interaction at the frontier of knowledge: fundamental research and applications*) in which the group for particle physics from the Faculty of Natural Sciences and Mathematics of the University of Montenegro participates. The results of the thesis will be obtained by analyzing experimental data from the CMS experiment led by a collaboration of which University of Montenegro has been a full member since 2017. Through the full membership, members of the collaboration have the right to use all the resources of this collaboration - all experimental data obtained with the CMS and the entire computer infrastructure is available to every doctoral student who is a member of this collaboration. Also, by acquiring a computer account at CERN, a student can use all databases with scientific publications in the fields of natural sciences, mathematics and engineering.

Mišljenje i prijedlog komisije

After the oral defense of the initial research, discussion and answers of the candidate to the questions, the Commission unanimously agreed that this is an original and challenging scientific research topic. During the Defense of Initial Research, the candidate showed a very high level of knowledge on the topic she is working on and the results she has achieved so far present a solid basis for continuing further research.
Therefore, the Commission recommends to the Council of Faculty of Natural Sciences and Mathematics and the Senate of University of Montenegro to accept this report and approve the proposed topic of the doctoral dissertation of the candidate Itana Bubanja, MSc.

Prijedlog izmjene naslova

Prijedlog promjene mentora i/ili imenovanje drugog mentora

(titula, ime i prezime, ustanova)
Planirana odbrana doktorske disertacije
2024.
Izdvojeno mišljenje
(popuniti ukoliko neki član komisije ima izdvojeno mišljenje) Ime i prezime ____________________
Napomena
(popuniti po potrebi)

ZAKLJUČAK		
Predložena tema po svom sadržaju **odgovara** nivou doktorskih studija.	**DA**	NE
Tema **je** originalan naučno-istraživački rad koji odgovara međunarodnim kriterijumima kvaliteta disertacije.	**DA**	NE
Kandidat **može** na osnovu sopstvenog akademskog kvaliteta i stečenog znanja da uz adekvatno mentorsko vođenje realizuje postavljeni cilj i dokaže hipoteze.	**DA**	NE

Komisija za ocjenu podobnosti teme i kandidata	
Dr Slobodan Backović, CANU, Crna Gora	Sl. Backović
Dr Ivana Pićurić, Prirodno-matemetički fakultet, Univerzitet Crne Gore, Crna Gora	
Dr Hannes Jung, DESY, Hamburg, Njemačka	H. Jung
Dr Laurent Favart, F.R.S.-FNRS, IIHE, ULB, Brisel, Belgija	Laurent Favart
Dr Nataša Raičević, Prirodno-matemetički fakultet, Univerzitet Crne Gore, Crna Gora	N. Raičević

U Podgorici, 28.03.2022.

DEKAN

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MP

PRILOG

PITANJA KOMISIJE ZA OCJENU PODOBNOSTI DOKTORSKE TEZE I KANDIDATA	
Dr Slobodan Backović	1. Today you showed new distributions only for muon pairs. What is the status of electron pair analysis ? 2.What kind of trigger logic is planed to be used for the measurements ?
Dr Ivana Pićurić	1. Where do you expect the most of improvement with the complete RUN 2 statistics ? 2. In your master thesis, you have done analysis of Drell-Yan lepton pairs from proton-proton collisions at 5 TeV. Do you plan to extend this analysis in your PhD thesis ?
Dr Hannes Jung	1. Do you understand why the peak of $\Delta\Phi$ is not more pronounced with increase of the dilepton invariant mass ? 2. Do you understand such a large difference in the cross sections at small pair p_T when using the same tune for underlaying event and multi-parton interactions ?
Dr Laurent Favart	Comments and discussion about the results shown and the questions asked by the committee members.
Dr Nataša Raičević	1. What is the present status of the nano-AOD ? Comments and discussion about the results shown and the questions asked by the committee members.
PITANJA PUBLIKE DATA U PISANOJ FORMI	
(Ime i prezime)	
(Ime i prezime)	
(Ime i prezime)	
ZNAČAJNI KOMENTARI	