Semester Report 4

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Precision electroweak measurements with the CMS detector at the LHC

Introduction

Precision measurements looking for small deviations in experimental observables due to the presence of some New Physics at a higher energy scale are potentially able to catch even the unexpected. In particular, measurements of electroweak diboson production can provide information on anomalous gauge couplings and thus point to certain extensions of the Standard Model (SM). Differential di-boson cross-section measurements – even in the absence of direct evidence for New Physics, such as the discovery of a new resonance – will contribute to our understanding of the SM gauge interactions and of electroweak symmetry breaking and challenge precision theoretical calculations. The LHC provides unprecedented statistics for these studies and thus acts as an electroweak-scale microscope to study gauge boson self-interactions.

Diboson production is a sensitive probe of electroweak symmetry breaking. In the Standard Model, the Higgs boson exchange contributes to the vector-boson scattering cross-section. Any difference in the Higgs couplings due to New Physics would thus affect the measured cross-section. Several BSM models, for example two-Higgs-doublet models or supersymmetric models with a light stop or slepton, predict enhanced di-boson production.

Differential cross-section measurements are valuable irrespective of whether New Physics is found at LHC or not. Enhanced production in the high-energy tail would provide a measure of anomalous gauge boson couplings. The study of the distributions of additional jets in di-boson events also offers a stringent test of the higher-order perturbative calculations within the Standard Model.

Diboson final states can also originate from Double Parton Scattering (DPS) and could thus be used to study the structure of the proton, as I will discuss below.

Summary of research work carried out in the previous three semesters

1. Physics validation using Minimum Bias and Z boson production samples

As the CMS collaboration requires all of its members to contribute to common experimental tasks, I am responsible for physics validation of new software releases on behalf of the Standard Model Physics Analysis Group (SMP PAG).

My first task is coordinated by the Physics Performance and Dataset (PPD) Group at CMS. The role of PPD is to ensure the quality of data that are provided to the physics analysis groups. They are responsible both for the quality of data being recorded during collisions, as well as after (re)processing with improved calibration. In the CMS experiment, the Data Quality Monitoring (DQM) is critically important for detector and operation efficiency, and for the reliable certification of the data for physics analyses. The main goal is to discover and pin-point problems occurring in detector hardware or reconstruction software promptly and with sufficient accuracy and clarity to reach high efficiency and excellent performance.

I am part of the Physics Data and Monte Carlo Validation (PdmV) organization collaborative effort, at which I work on validating new software releases that include changes from many developers in many packages. This should be done before using a release for official MC production or data reconstruction. A set of samples (CMS data, "fullsim" detailed Geant4 Monte Carlo (MC) simulation and "fastsim" parametric less CPU intensive MC) is produced for every release to be validated for each Physics Analysis Group (PAG). I perform validation tasks by verifying typical physics performance plots that are produced with standard physics analysis procedures. I compare target plots vs. reference plots, and then summarize the findings in validation reports. I am responsible for Forward, Small-x and QCD-Physics (FSQ) and Standard Model Physics (SMP) validation based on Minimum Bias and $Z \rightarrow l^+l^-$ physics samples.

In case of observed differences, I investigate if they are *expected* due to developments, such as improvements in calibration or reconstruction software or other known changes, or if they are *unexpected* (for example, a result of mistakes introduced in the new version) and cause problems or decrease performance. In the reports, I describe the differences and their origin if found.

2. WW production from double-parton interactions

Hard-scale double parton interactions where two partons interact in the same proton-proton collision are becoming more and more accessible at the LHC with the increase in center of mass energy to 13 TeV and the excellent performance of the machine providing larger datasets.

Under the assumption of the factorization of the double parton density function, the cross section of a double parton scattering (DPS) process can be written as

$$\sigma_{AB}^{DPS} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

where, A and B denote the single parton scattering (SPS) processes, and σ_A and σ_B their respective SPS cross sections. The factor n is unity if processes A and B are the same, and $n = 2$ if $A \neq B$. The parameter σ_{eff} is related to the extent of the parton distribution in the plane orthogonal to the direction of motion of the protons.

I joined the measurement of the process in which two W bosons of the same-charge are produced via double parton interactions based on the CMS full Run 2 dataset. This process provides interesting experimental features if the W bosons decays leptonically, by reducing standard model (SM) backgrounds. While there is evidence for the presence of this production mode, it has yet to be confirmed at 5σ. The measurement of its cross section can provide valuable input to Monte Carlo (MC) generators on whether the model for multi parton interactions is correct. Furthermore, this process constitutes a background for studies of vector boson scattering and anomalous vector boson couplings and for searches for new physics such as electroweak (EWK) searches for supersymmetry (SUSY), and therefore a measurement can provide increased confidence in background estimations in these analyses.

In this work I reproduced the 2016 and 2017 events count, as a starting point toward reaching the 5σ discovery limit with the full run 2 dataset, i.e., including the 2018 dataset.

Here I compared different generator samples of the DPS signal in the $\mu^{\pm}\mu^{\pm}$ or $e^{\pm}\mu^{\pm}$ final states for the kinematic variables: transverse momentum (p_T) of the leading (l_1) and the subleading (l_2) leptons, angular variables using the lepton pseudorapidities (η) and azimuth angle (ϕ) such as $|\eta_1 + \eta_2|$, $\eta_1 \bullet \eta_2$, $\Delta\phi(l_1, l_2)$, $\Delta\phi(ll, l_2)$, the missing transverse momentum E_T^{miss}, its azimuth direction with respect to the leading lepton $|\Delta\phi(l_1, E_T^{miss})|$, and various transverse mass variables calculated from the lepton and the missing transverse momentum vectors $m_T(l_1, l_2)$, M_{T2}^{ll}, $m_T(l_1, E_T^{miss})$. The events with same-sign leptons are analyzed with a moderate requirement on the missing transverse momentum, a veto on jets stemming from b-quarks as well as allowing only a low number of jets. The same-sign requirement reduces the background contribution to a minimum and the kinematic differences between the WW DPS process and the remaining background can be exploited to optimize the signal-to-background ratio.

Description of research work carried out in current semester

1. Physics validation using Minimum Bias and Z boson production samples

I am still part of the Physics Data and Monte Carlo Validation (PdmV) team and fulfil my responsibility of physics validation of new software releases on behalf of the Standard Model Physics Analysis Group.

2. Double-parton scattering studies in same-signWW production with full Run2 dataset

In this semester I applied the analysis on the new data reprocessed with improved calibration as well as tried new analysis methods to reach the 5σ discovery limit by also including the full run 2 dataset.

The same-sign requirement reduces the background contribution to a minimum and the kinematic differences between the WW DPS process and the remaining backgrounds can be exploited to optimize the signal-to-background ratio. The most important remaining background is the fully-leptonic WZ process in which one of the leptons from the decay of the Z boson is lost due to acceptance or reconstruction, or the Z boson decays to two tau leptons, one of which decays leptonically to provide the second lepton for the same-sign pair, while the other tau lepton decays hadronically. Since this process is theoretically well understood, it is taken from MC. When losing one of the leptons from the Z boson decay, this process becomes kinematically very similar to the signal process and therefore a multivariate discriminant is trained to increase the separation as much as possible.

The SPS $W^{\pm}W^{\pm}$production includes two additional partons and its cross section is therefore suppressed at the matrix-element level. The absence of jets in the $W^{\pm}W^{\pm}$

production via DPS at LO in perturbation theory provides an additional handle to reduce the contributions from the SPS backgrounds by introducing an upper limit on the number of jets. Moreover, when both W bosons decay leptonically, this event exhibits a clean final state in the detector, and the excellent reconstruction and resolution of leptons in the CMS detector provides an accurate measurement of the WW DPS cross section.

The other main background component stems from so called “fake”-leptons, which are leptons not originating directly from a hard-scatter boson, but where leptons are reconstructed as such while originating from either heavy flavor decays or from mis-reconstruction of jets as leptons. This background is estimated using a fully data-driven method from control regions in data. A second BDT classifier is trained against this background process to increase signal to background discrimination.

Results for some BDT variables of the present work for the full run2 data (2016, 2017 and 2018) are shown in Fig. 1.

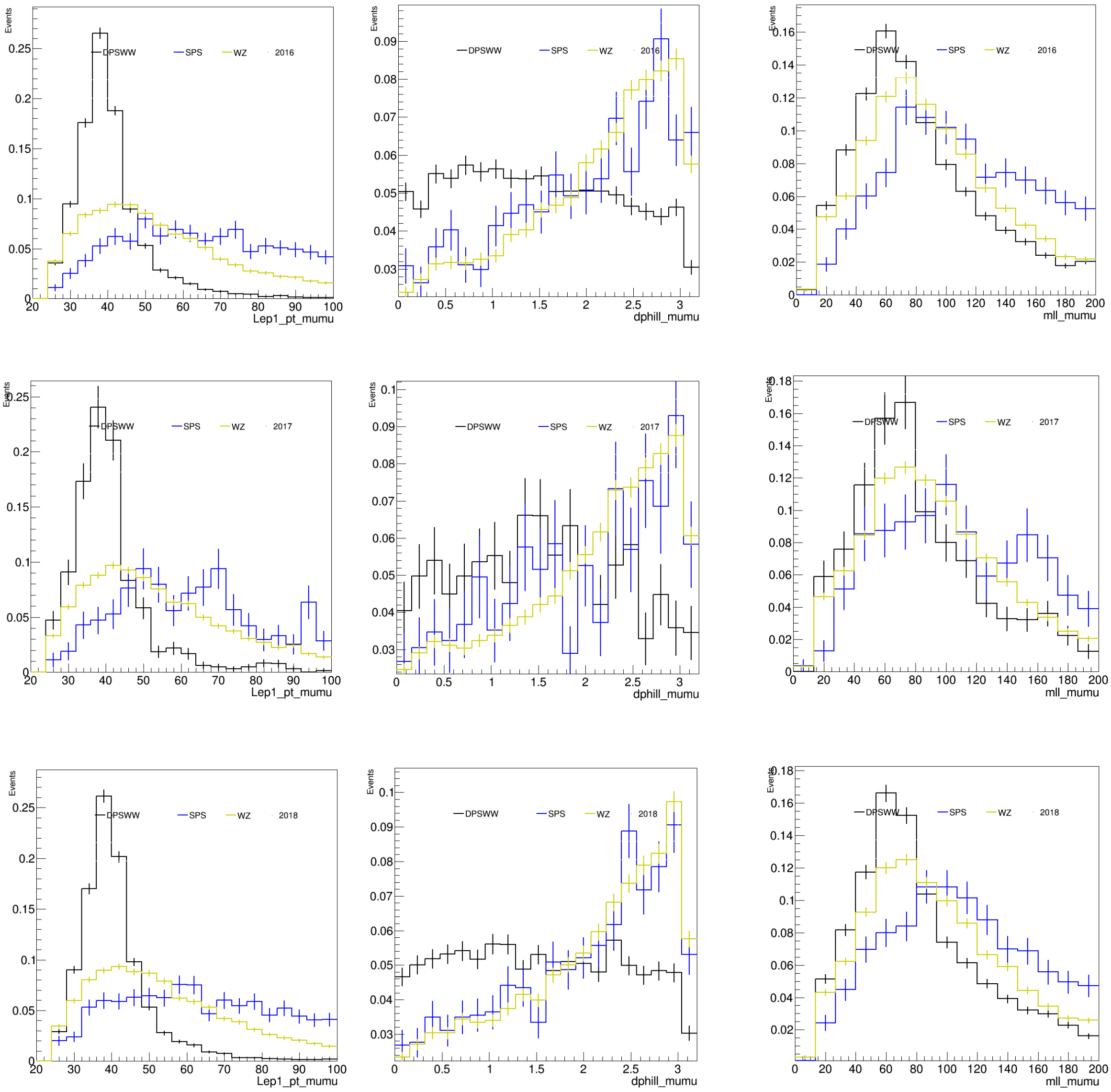

Figure 1 Comparison between signal (DPSWW) and background (SPS and WZ) distributions in the three years from 2016-2018 for the dimuon pT, the azimuth angle difference for the two muons and the dimuon invariant mass.

Publications

“Double-parton scattering studies in same-sign WW production with the full CMS Run2 dataset” is expected to be submitted for publication at the end of this year. A full report was presented (including my contribution) in the CMS SMP WW subgroup meeting on March 23, 2021 and the internal analysis note is under preparation.

Studies in current semester

To fulfill the credits requirements, I followed one course this semester and passed an exam for a course followed previously:

- Beyond the Standard Model (6 credits)
- Experimental Methods in Particle Physics II (exam course, 6 credits)

Attendance on seminars, meetings, workshops and schools

- Weekly ELTE CMS meetings, ELTE Ortvay seminars, ELTE Particle Physics seminars.
- CMS Virtual Data Analysis School, September 23 – 30 2020.
- PDD Physics Validation Weekly meetings
- PPD Workshop Spring 2021, 22-25 March
- ELFT Winter School Physics beyond the Standard Model: Modern Approaches. February 1 – 5, 2021