Chapter 7

Summary

Persistent developments in various physics models lead to the conceptual foundation of today's high energy physics. These underlying physics models revolutionized our understanding about the matter and its constituents. These models have been developed in great depth even beyond the standard model (SM), but we still miss a decisive input that would be able to answer all the unresolved key questions. In this regard, the Large Hadron Collider (LHC) at CERN has been built to bring us closer to the understanding of matter. The LHC is the world's most powerful particle accelerator and is designed to carry out proton-proton (pp) collisions at a center-of-mass energy of 14 TeV. The discovery of a particle that behaves similar to the SM Higgs boson is a triumph for 20$^{\text{th}}$ century physics. The goals of the energy frontier are to investigate high energy and high luminosity collisions delivered by the LHC using proficient general purpose detectors such as the Compact Muon Solenoid (CMS) detector for leading physics analyses in characterization of the Higgs Boson, and to make extensive studies of electroweak and beyond the standard model phenomena.

The physics analysis described in this thesis are based on the data collected by the CMS experiment during 2012 at the LHC. The work reported is directed towards a twofold aim: (a) fabrication, characterization, and testing of resistive plate chamber (RPC) detectors for the CMS muon detector systems (b) analysis of 8 TeV pp collision data collected using the CMS detector. A brief summary and outcomes of both these tasks are given in the following Sections.

7.1 Assembly and Characterization of RPCs

Muons act as a clean signal to record interesting physics events over the huge background processes at the LHC. Highly redundant and robust CMS muon detector system is designed to provide efficient muon triggering and precise measurement of muon kinematics within a pseudorapidity region defined by $|\eta| < 2.4$. RPCs constitute an important part of the CMS muon detector system and are employed both in the barrel and endcap regions. In the course of first long shutdown (LS1) period of the LHC, various subdetector components of the CMS detector were upgraded to withstand the increased collision rate at the LHC. Before LS1, only three layers of RPCs were installed in the three existing endcap disks, despite the fact that Technical Design Report (TDR) for the CMS muon trigger anticipated to have four layers of RPCs in pseudorapidity region 1.2–1.6. The fourth layer of RPCs, referred to as CMS RE4 (CMS RPC Endcap Disk 4), was added to the CMS detector during LS1. The CMS muon detector system was upgraded with 144 RPCs in the endcap disks (Disk$\pm$4).

India-CMS Collaboration contributed to the CMS RE4 upgrade project for the assembly and characterization of the RE4/2 RPCs. Two dedicated and independently stationed Indian laboratories, one at Nuclear Physics Division, Bhabha Atomic Research Center, Mumbai and another at Panjab University, Chandigarh, decided to carry out this task. Both the laboratories are equipped with necessary and up-to-date experimental and technical facilities for this purpose. The hardware studies reported in this thesis are carried out at Department of Physics, Panjab University Chandigarh. The performance of newly installed RPCs in the CMS RE4 region is evaluated during the 13 TeV Run of the LHC in the year 2015. We have participated in the fabrication, assembly, and characterization of RPCs at both these laboratories.

In the CMS RE4 regions, the used RPCs have a trapezoidal double-gap geometry. Each of these RPCs consists of three different bakelite gas gaps: two in the top layer and one in the bottom layer. The button and edge spacers are used to maintain a uniform gap between the two bakelite sheets. The gas gaps are fabricated in South Korea and transported to the assembly sites, followed by mechanical and electrical tests at the assembly sites. After passing the visual inspection, the gas gaps are subjected to the gas leak test at over-pressure of 5 mbar and 20 mbar. The change in over-pressure with time is continuously monitored and is found to be within prescribed limits set by the CMS Collaboration. Spacer tests are performed on all the gas gaps to check the integrity of spacers. The gas gaps after passing these mechanical tests qualify for the electrical tests. These electrical tests include the measurement of their V-I characteristics, dark current, and stability over a longer period. The qualified gas gaps are then assembled into an RPC, fully integrated with front-end electronics and Cu-cooling system. The performance of these assembled RPCs is judged in terms of their strip profile, cluster size, and detection efficiency with a standard RPC gas mixture at 40% humidity. All the RPCs are found to have nominal cluster size and good strip profile. All these RPCs have a detection efficiency $> 95\%$, which is compatible with the CMS standards. These RPCs are then successfully installed at the CMS detector in the summer of 2014. The CMS RPC system is performing well and is delivering good data for the physics analyses. The average efficiency of RPCs in the CMS RE4 region is found to be $\sim$94% with an average cluster size of 1.87. The addition of CMS RE4 RPCs has increased the overall robustness of the CMS muon spectrometer and improved the muon reconstruction efficiency in the pseudorapidity range $1.2 < |\eta| < 1.8$. With the upgraded CMS muon detector, muon triggering efficiency has increased from 80% to 95%.

7.2 Study of DPS Processes Using Same-Sign WW Events

Protons are composite objects, made up of quarks and gluons (collectively called partons). When two protons collide, there is a significant possibility to have more than one hard parton-parton interaction within a single pp collision. The simultaneous occurrence of two hard partonic interactions, namely double-parton scattering (DPS), is the simplest realization of multiple-hard partonic interactions (MPI). DPS is expected to be more important relative to the single-parton scattering (SPS) processes at the LHC. In this thesis, we have investigated the DPS processes using same-sign WW events. DPS is an interesting signal process in its own right, as it sheds light on the correlations between the partons inside the proton. Additionally, DPS processes can give rise to important background contributions to the interesting SM and rare beyond the standard model processes. The production of W boson pairs with their successive decay into leptons offers a distinguishable signal at the LHC. Only same-sign WW events are scrutinized to suppress the contributions from SPS processes.

The data samples used in this analysis have been recorded using the CMS detector, during the pp collisions at $\sqrt{s} = 8\,\text{TeV}$ corresponding to an integrated luminosity of $19.7\,\text{fb}^{-1}$. The decay of two W bosons is considered into electron-muon and dimuon pairs. The dielectron final states are not considered; as these final states are highly contaminated by the background contributions coming from the charge misidentification of electrons and jets misreconstructions. The electron-muon final states require the presence of an electron (muon) with $p_{\mathrm{T}} > 17\,\text{GeV}$ and another muon (electron) with $p_{\mathrm{T}} > 8\,\text{GeV}$. The dimuon events are selected by requiring the leading muon $p_{\mathrm{T}} > 17\,\text{GeV}$ and the subleading muon with $p_{\mathrm{T}} > 8\,\text{GeV}$. Other kinematical cuts are applied to suppress various background contributions.

A set of DPS-sensitive observables is defined based on DPS event topolo-

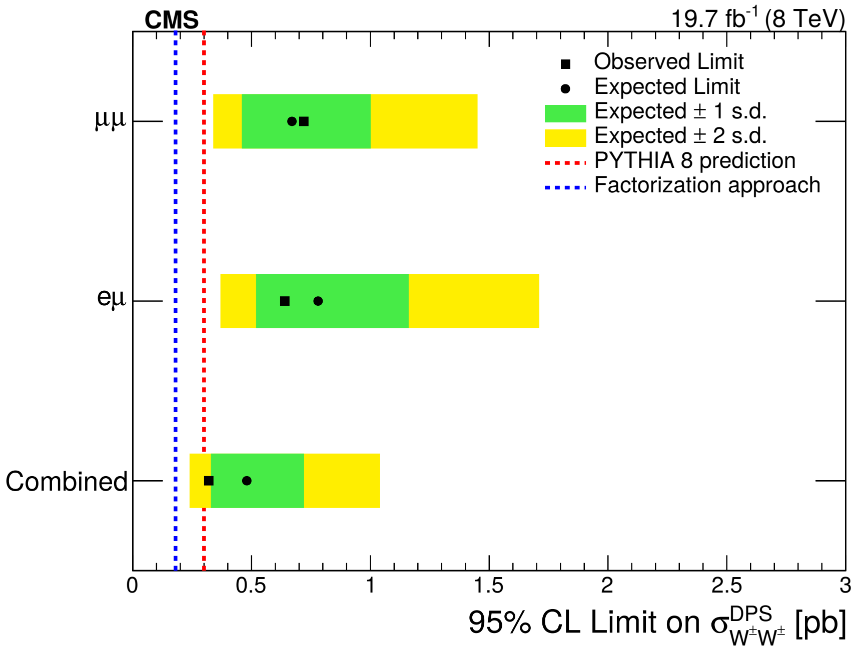

Figure 7.1: 95% CL limit on the $\sigma^{\mathrm{DPS}}_{\mathrm{W}^{\pm}\mathrm{W}^{\pm}}$ for the dimuon and electron-muon final states along with their combination.

gies and are combined using a multivariate analysis based on boosted decision trees (BDT). Previous DPS analysis have been performed using conventional DPS-sensitive observables and this is the first DPS analysis carried out using multivariate approach. The BDT discriminant is found to have maximum sensitivity in comparison to the individual variables. The shape of the BDT discriminant is used to perform statistical analysis. The data are analysed separately using the dimuon and electron-muon final states and the obtained results are then combined to increase the sensitivity of the analysis. No significant excess over the SPS background events is observed. Based on the combined analysis, an observed upper limit of 0.32 pb is placed on the inclusive same-sign WW production via DPS ($\sigma^{\mathrm{DPS}}_{\mathrm{W}^{\pm}\mathrm{W}^{\pm}}$) at 95% confidence level (CL). This limit is more stringent as compared to the ones placed based on the analysis of individual final states. Figure 7.1 summarizes the sensitivity of the BDT-based analysis for different final states. The main outcome of the DPS studies is the extraction of effective cross section (σ_{eff}) parameter, which carries the information on the spatial distributions of the partons inside the protons. Using

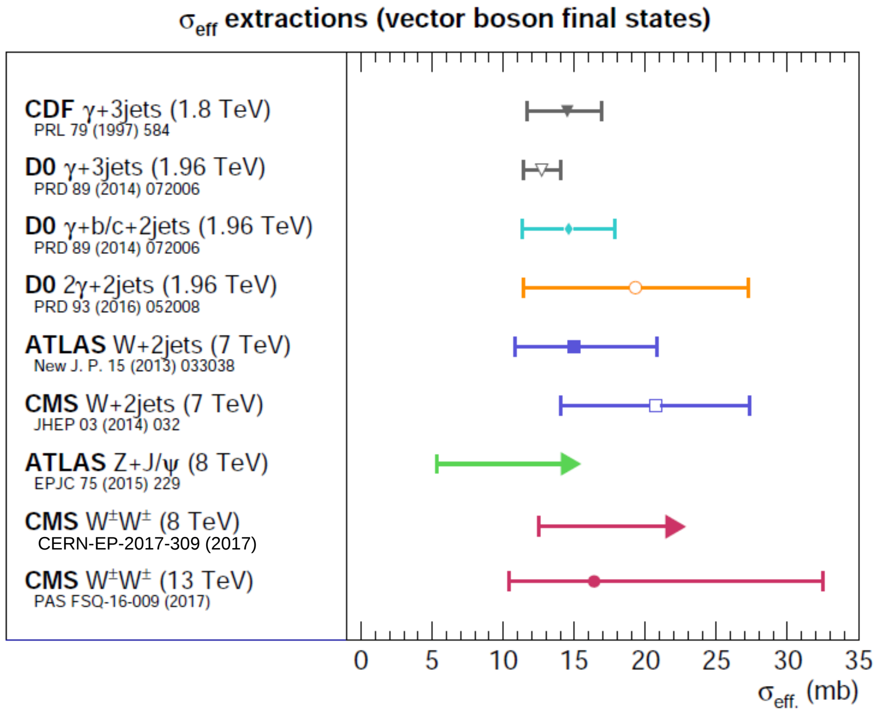

Figure 7.2: Measurement of σ_{eff} at different center-of-mass energies using different DPS processes. Different markers represent results taken from mentioned references.

the observed limit on the $\sigma^{\text{DPS}}_{\text{W}^{\pm}\text{W}^{\pm}}$ and the factorization approximation, a lower limit of 12.2 mb is placed on σ_{eff}. The obtained limit on σ_{eff} is found to be compatible with previous measurements using different final states at different collision energies (Figure 7.2).

7.3 Outlook

Measurements of diboson final states constitute an important baseline for future studies and investigations at the LHC. These final states are probed to test the predictions of SM and look beyond it. It is customary to perform DPS studies, which savour a increased production rate in the high luminosity collisions at the LHC. DPS processes can result in substantial contributions to the production of interesting physics events in different phase space regions. Due to suppressed background contributions from the SPS processes, the production of pair of same-sign W bosons is a sensitive channel to study the DPS processes. Using the total integrated luminosity available at 8 TeV and very small expected DPS signal, limits are placed on $\sigma^{\mathrm{DPS}}_{\mathrm{W^{\pm}W^{\pm}}}$ and σ_{eff}. The increased luminosity and collision energy at the LHC has allowed to accumulate much more statistics than the Run-I analysis. The same analysis has shown some signal sensitivity with pp collision data at $\sqrt{\mathrm{s}}$ =13 TeV. Studies are ongoing to analyse more data which could lead to the first DPS signal with this final state. The measurements of effective cross section parameter would be an extra opportunity to check its dependence on the process type and collision energy. Once its dynamics are confirmed, several avenues will open up. It can be used to estimate the DPS production cross section for rare physics processes based on the factorization approach. Deviations observed between the experimentally measured values of DPS cross section and the ones calculated based on the factorization approach, can point towards the need of improved theoretical predictions. Additionally, the multivariate analysis strategy developed during this analysis could be employed to study DPS processes using other final states as well. We intend to pursue these investigations in the future.