CHAPTER 7

Summary

In this work a detailed overview of the analyses done in the scope of the CMS Forward Physics Analysis Group with the data taken during the LHC Run1 was presented. The FWD PAG in Run1 was composed of three subgroups – exclusive, forward jets (including underlying events studies) and diffractive. The author of this work was the first convener and a coordinator of the analyses in the two of these subgroups.

The first step in the FWD PAG studies was a measurement of the underlying event activity and a comparison with existing Monte Carlo models and tunes. These studies are important as they:

- Help to better understand soft and semi-hard component of high energy interactions. These components are described by various models within Monte Carlo generators. Parameters of the models can be selected in a given range to best fit the data. The process is called tuning. The analyses results can be therefore included as an input to the future tunes.
- Enable proper jet energy scale definition for the forward calorimeters and description of its dependence on pile-up. In the process of jets reconstruction the energy from an underlying event and the energy produced by additional pile-up interactions has to be effectively subtracted.
- Improve selection of the large rapidity gaps present in diffractive events. The underlying event, e.g. MPI, is responsible for production of additional particles filling the rapidity gap. Moreover, the rapidity gap can be destroyed by activity produced in other interactions present in a given event (pile-up). Therefore good description of the activity in the minimum bias events provides a tool to correct for at least some of the effects that reduce a probability of a large rapidity gap survival.
- The same applies to a selection of exclusive interactions. The exclusivity criteria may be compromised by additional activity produced in the same event as a part of the underlying event (e.g. proton dissociation) or coming from pile-up interactions.

As indicated above a good understanding of the underlying event has a strong influence on all other analyses described in this work – jet activity, diffraction and exclusive production search. A forward region is very important for a proper underlying event measurement as most of the UE activity is contained at large rapidities. Moreover, it is a region where different components of the UE interfere – e.g. MPI and beam remnant. This was clearly visible in the analysis of the energy flow in the CASTOR acceptance at different center-of-mass energies, Section 3.4. To facilitate handling of the experimental data in the process of tuning, results are translated into **R**obust **I**ndependent **V**alidation of **E**xperiment and **T**heory (RIVET) toolkit format [249]. The RIVET collects in a database results of a vast number of analyses from various (LHC and non-LHC) experiments. It allows to use these results in a tuning process and to compare them easily with different Monte Carlo models. The forward energy flow measurement was among the first measurements from the CMS to be added to the RIVET database. The results presented in Chapter 3 were used as an input to the tuning process done by various groups. The latest of these efforts (tunes for PYTHIA8, PYTHIA6 and HERWIG++) are described in [250].

The main goal of the forward jets measurement was to find an evidence for the appearance of processes governed by the BFKL dynamics. High center-of-mass energy and access to high rapidities provide means to look for the BFKL. A series of forward jets measurements was conducted, starting from the basic analysis of the inclusive forward jets cross section and then moving to various measurements of correlations between jets. The correlations are sensitive to the appearance of additional radiation in events with forward jets. It was found that the result on the inclusive forward jets cross section, important also for the measurement of the PDFs at low-x, is encumbered with large errors resulting from the jet energy scale uncertainty. Therefore it cannot be used to disentangle BFKL/DGLAP dynamics nor help to improve determination of the PDFs. An interesting result is coming from the K-factor analysis, Section 4.7. An assumption that this observable should be strongly susceptible to the BFKL effects is found to be not true. The experimental distributions are very well fitted with PYTHIA6 and PYTHIA8, while BFKL motivated Monte Carlo models (CASCADE and HEJ) do not agree with the data. This could be caused by a selection of jets with relatively high transverse momenta ($p_{\mathrm{T}} > 35$ GeV). This cut probably lowers the influence of the BFKL dynamics on the observables. The Mueller–Navelet dijets azimuthal decorrelation was proposed as an observable especially sensitive to the BFKL effects. In this work a comprehensive analysis of the decorrelations of the MN dijets produced at 7 TeV center-of-mass energy was described. To perform this analysis in a widest possible rapidity range, a dedicated forward-backward dijet trigger was proposed and implemented. The results are in a qualitative agreement with both – DGLAP and BFKL motivated Monte Carlo models. However the quantitative agreement is much worse, as none of the models is able to describe all the aspects of the measurement within the experimental uncertainties. The conclusion is that the effective hunt for the BFKL effects requires a comparison of the forward jets data collected at different center-of-mass energies. For data collected in Run2 at $\sqrt{s}$ =13 TeV the MN dijets analysis is now ongoing at the Warsaw University.

Diffractive interactions is a topic that draws strong attention on both sides – theoretical and experimental. Experimental definition of diffractive events, in the absence of the close to the beam detectors that could register outgoing protons, is based on a detection of large rapidity gaps. The survival of the LRG is susceptible to the underlying event activity accompanying a diffractive interaction, pile-up and detector effects. All of these components produce additional activity (particles or detector noises) that could fill and destroy LRG. Discussion presented in Chapter 5 was first focused on soft diffraction events, without a demand on a production of an object defining a high energy scale. These events should be in fact called “minimum bias” diffractive events, as from the selected sample hard diffraction is not removed. However, the hard diffraction component is by a few orders of magnitude smaller than the soft one. Therefore its presence in the sample can be neglected. In the CMS soft diffraction analysis both, single diffractive dissociation and double diffractive dissociation components, are studied and their cross sections measured. The results are compared to the models that predict strengths of the diffraction components at different $\sqrt{s}$. The models are in accordance with the experimental CMS data. Then the hard diffraction CMS studies were described. Production of high-p_{T} dijets and W or Z bosons in events with LRG was discussed. A clear evidence of diffractive dijets production was found and a LRG survival probability was estimated taking predictions from various LO and NLO models. For the sample containing bosons a diffractive production mechanism was much more difficult to be proven. However in the course of the presented analysis a strong indication towards a presence of this mechanism in the selected sample was shown. Finally, a group of events in which a LRG is present in between two jets was selected – the jet-gap-jet topology. In these events a hard color singlet structure is exchanged between the two jets. PYTHIA6 is not able to describe the experimental results as it does not simulate hard color singlet component. A simplified BFKL approach to the simulation of this component is included in HERWIG6. It is found that a mixture of PYTHIA6 and HERWIG6 (with additional events re-weighting) provides a good description of the data. This result is very important as it provides the strongest so far support for the presence of the BFKL dynamics in the CMS data.

Central exclusive production can be induced by $\mathbb{PP}$, $\gamma\mathbb{P}$ or $\gamma\gamma$ interactions. In the first two channels the process corresponds to a specific diffractive interaction with a final state well under control. Examples of such interactions are gg $\rightarrow \gamma\gamma$ or $\pi^+\pi^-$ CEP. The first of these was looked for and no event candidate was found. This allowed to set an upper limit for the cross section for the reaction. The limit is a little bit above limits coming from theoretical predictions. In case of $\pi^+\pi^-$ production a large number of events was collected and a cross section for production was calculated. A scan for new states in the invariant mass of the system was performed. Two possible new structures at 1.6 and 1.9 GeV were spotted. However, due to the not perfect background modeling it was not possible to declare the significance of these structures and therefore to claim discovery. Central exclusive production in $\gamma\gamma$ interactions was studied in channels leading to the exclusive dileptons production. In both final state configurations ($\mu\mu$ and ee) signals were found and production cross sections calculated. They are in a very good agreement with the QED predictions. A dedicated study was performed with $\gamma\gamma \rightarrow \mathrm{W}^+\mathrm{W}^-$ central exclusive production. The study led to the upper limit on the anomalous quartic gauge coupling, which is the most stringent experimental limit put so far. In 2014 a new CMS detector component was approved – **C**MS-**T**OTEM **P**recision **P**roton **S**pectrometer (CT-PPS) [251]. The detector, which in 2016 started to record the data, extends the tracking coverage to the close to the beam region and it is designed to be fully operational during high luminosity data taking. It will allow to directly detect events with the two interacting protons intact. Therefore it will provide new ways to study diffraction and especially enable selection of exclusive production even in a high pile-up environment. The ultimate goal is to collect in the future 100 fb^{-1} of data with the CT-PPS system. With this amount of data not only all presented results will be highly improved but also exclusive production of Higgs boson will be in reach. Moreover, a search for CEP of new states, e.g. supersymetric particles, will be performed.

Forward Physics Analysis Group active in Run1 was the smallest of the physics analysis groups working at CMS. Nevertheless, as presented in this work, its physics programme was broad and fruitful. The analyses were performed at the energies never achieved before in accelerators, but also with the broadest acceptance in the rapidity ever provided by the experimental setup. The Run2 started in 2015 with $\sqrt{s}$ =13 TeV. Most of the analyses performed in the scope of the FWD PAG will be repeated at this higher energy. Unfortunately, the main emphasis in Run2 is on a search for new physics and therefore on collecting as much data as possible. Thus periods of low luminosity running is highly restricted limiting the exclusive and diffractive analyses. Luckily, with the new detectors, e.g. CT-PPS, and a planned close collaboration with the TOTEM experiment, this drawback is minimized. Therefore it is expected that even more interesting results on forward physics will be published on Run2 data.

There is also an opportunity to repeat some of the presented analyses with the same 7 or 8 TeV data but better understanding of the CMS detector. It is especially important for the forward energy flow and the inclusive forward jets analyses. The results of these are dominated by large systematic uncertainties. Much deeper studies of the detectors performance were done after these analyses had been published. Therefore it is expected that the systematic uncertainties will be reduced if these analyses are repeated with better e.g. jet energy scale tuning. This action is however dependent on the availability of human resources which are at the moment fully allocated in the 13 TeV data analyses.