Chapter 1

ATLAS results on diffraction and exclusive production

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Various aspects of forward physics have been studied by the ATLAS collaboration using data from Run I at the LHC. In this text, main results of three published analyses are summarized, based on data from proton-proton collisions at $\sqrt{s} = 7$ or 8 TeV collected between 2010 and 2012. One analysis deals with diffractive signature with at least two jets in the final state, the other two study exclusive production of a pair of leptons or W bosons.

1. Introduction

A better understanding of diffraction and exclusive processes at LHC is not only useful on its own (an experimentalist’s view on the diffraction physics program and early exclusive measurements at LHC is discussed in and respectively, it is also profitable for other LHC analyses where they form a non-negligible background. Both types of processes were measured at HERA and Tevatron but cross sections are still known with a limited precision at LHC. Furthermore, results of such measurements are important in various Monte Carlo tunes. All three presented processes have a common feature regarding the final state, namely the existence of rapidity gaps, i.e. regions in detector devoid of hadronic activity. The large rapidity gaps, or intact proton in the final state, refer to the colorless exchange. Since the intact proton was not measured in the data used in these analyses (the special forward proton detectors around the ATLAS detector were only installed during the Run II), we are left with two approaches to select the signal and reduce the background. Either we select only events with large

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rapidity gaps in the central detector and then we are forced to concentrate on low pile-up and measure processes with large cross-sections; or we require no tracks and vertices around the lepton vertex and then we can also use data samples with a large pile-up and hence access processes with low cross-sections. The former approach was used in the analysis of diffractive dijets where used data come from first runs of LHC with a relatively low pile-up. The latter approach was then used in the remaining two analyses where much larger data samples were analyzed but also with a more significant amount of pile-up.

The processes with intact protons are divided into two broad classes. The photon-induced processes which are calculable using Quantum Electrodynamics (QED) include QED diffractive processes such as Single dissociation (SD), Double dissociation (DD) and QED exclusive processes, which can be calculated with a precision of down to 2% (based on the Equivalent photon approximation (EPA)) but where proton absorptive corrections can reach up to 20%. The QED exclusive processes with $l^+l^-$ or $W^+W^-$ in the final state are the signal in two analyses reported in this text and their Feynman diagrams are shown in Fig. 1 left and middle.

The second class of processes is formed by parton-induced processes calculable via Quantum Chromodynamics (QCD) and including SD, DD and Double Pomeron Exchange (DPE) processes for which we also need to consider the so called soft survival probabilities if we study them at hadron colliders. The QCD exclusive processes are not discussed in this text. The process of interest in the remaining analysis reported here is dijet production in SD events, see Fig. 1 right.

Fig. 1. Feynman diagrams for the signal processes of analyses reported in this text: left) QED $\gamma\gamma \rightarrow l^+l^-$, middle) QED $\gamma\gamma \rightarrow W^+W^-$ and right) SD dijets.
2. Diffractive dijets

Dijet events with large rapidity gaps between the intact proton (or the edge of the central detector) and the dijet system were already studied at HERA and Tevatron. In the CDF measurement a huge factor of discrepancy (~10) between the measured data and theory predictions based on diffractive parton density functions (dPDF) measured at HERA was observed. This discrepancy translates into the fact that measured dPDFs are not universal, in other words that the factorisation is broken. This is usually explained by rescattering of the dissociated system with the intact proton and the amount of this discrepancy is often called rapidity gap survival probability or simply soft survival probability, $S^2$. In most of cases at HERA the factorisation holds and hence $S^2 \approx 1.0$, since it is the photon, a much simpler system than the proton, that enters the diffraction reaction and hence no other rescattering is expected. Nevertheless also at HERA the factorisation may be broken in special cases where this photon has time to develop its structure and hence to be resolved. A natural question thus is what value of $S^2$ we can expect for the same process, dijets with rapidity gap, at LHC. It should be, however, stressed that the concept of $S^2$ is not well-defined theoretically. In some models this probability is embedded in amplitude calculations, in other models it is possible to factorise it. In any case, this quantity depends on the process studied and on kinematics. In it was obtained by comparing the data to the Pomwig model after subtracting from data the background from non-diffractive processes (ND) and DD using Pythia 8.1. The measured value is $S^2 = 16 \pm 4 \pm 8 \%$ with rather large systematic uncertainties coming from model dependence. Results that are easier to interpret are corrected cross-sections as functions of the forward gap size, $\Delta \eta_F$ and the fraction of four-momentum of the incident proton carried by Pomeron, $\xi$. From Fig. we can see that the gap plateau observed and expected in the gap analysis with no jet requirement is not observed here, which can be simply explained by the topology: the presence of at least two jets, each with a radius $R = 0.6$ does not leave much space for large gaps. Fig. also provides a comparison of the data with Pythia 8.1 where the ND contribution is normalized to match the data in the first $\xi$ bin and the SD and DD contributions are used with default cross-sections. The striking feature of Pythia 8.1 model is that the sum of ND, SD and DD contributions describes the data satisfactorily, i.e. with $S^2 \approx 1.0$. We also see that the ND contribution extends to fairly large gaps and small $\xi$ values.
3. Exclusive dileptons

In analysis\cite{10} the selection focused on electron and muon pairs produced exclusively, i.e. with no other activity around the production vertex in the central detector. This is a standard candle process thanks to its simple final state which can also be used for a luminosity calibration as well as for alignment and calibration of forward proton detectors AFP\cite{8} and CT-PPS\cite{9}.

The cross-sections, however, are small and hence only calibration/alignment over larger data taking periods would be possible. A key requirement is the so called exclusivity veto demanding no tracks with transverse momentum $p_T > 0.4$ GeV from the lepton vertex and in addition no tracks and vertices within at least 3 mm from the longitudinal isolation of the lepton vertex. Then after requiring the dilepton mass to be in a window of 70 and 105 GeV and restricting the lepton $p_T$ to be below 1.5 GeV, two acoplanarity distributions are made, namely $1 - |\Delta\phi_{e^-e^+}|/\pi$ and $1 - |\Delta\phi_{\mu^+\mu^-}|/\pi$ where data are compared to predictions of Herwig++ for exclusive, of LPAIR for SD and of Powheg and Pythia for DD and Drell Yan processes. The best description of the data is reached when the exclusive and SD contributions are scaled by factors 0.863 and 0.759, respectively, for the $e^+e^-$ pair, or by 0.791 and 0.762, respectively, for the muon pair. It is important to note that these scaling factors were found in agreement with those predicted in Ref\cite{11}.

The measured fiducial cross-sections for the exclusive $\gamma\gamma \to l^+l^-$ are $\sigma_{\text{excl}}(\gamma\gamma \to e^+e^-) = 0.428 \pm 0.035$ (stat) $\pm 0.018$ (syst) pb.
and $\sigma_{\text{excl}}(\gamma\gamma \rightarrow \mu^+\mu^-) = 0.628 \pm 0.032 \text{ (stat)} \pm 0.021 \text{ (syst)} \text{ pb}$. These values are found in a very good agreement with cross-sections based on EPA and corrected for absorptive corrections which range around 20% as well as with CMS measurement (see Fig. 3).

Fig. 3. Comparison of the ratios of measured (red points) and predicted (solid green lines) cross-sections to the uncorrected EPA calculations (black dashed line). Taken from Ref. [10]

4. Exclusive W bosons

The analysis described in Ref. [12] aims at estimating anomalous quartic gauge couplings ($aQGC$) $\gamma\gamma WW$ and collecting first candidates of exclusive Higgs boson decaying into the $W^+W^-$ pair decaying further to $e^\pm\nu\mu^\mp\nu$. This analysis profits from the measurement of the exclusive leptons presented in the previous section. Again the key requirement is the exclusivity veto described above, only the dilepton vertex longitudinal isolation is required to be less than 1 mm because in this sample data are more contaminated by pile-up. Similarly also the acomplanarity distributions are constructed, from which a ratio of observed to predicted QED exclusive events is extracted to be 0.76 which is in a reasonable agreement with values obtained in the dilepton analysis. Non-existent simulation of SD and DD $\gamma\gamma \rightarrow W^+W^-$ processes is accounted for by multiplying predicted QED exclusive $\gamma\gamma \rightarrow W^+W^-$ events by a factor 3.3 obtained using exclusive $\gamma\gamma \rightarrow l^+l^-$ events in the region $m_{ll} > 160 \text{ GeV}$ from Herwig+++. This number is found to be in agreement with that predicted
The measured cross-section for the process $\gamma\gamma \rightarrow W^+W^-$ in Standard Model extrapolated to the full $W^+W^- \rightarrow e^\pm \mu^\mp X$ phase space is $\sigma_{\text{extr}}(\gamma\gamma \rightarrow W^+W^-) = 6.9 \pm 2.2 \text{ (stat)} \pm 1.4 \text{ (syst)} \text{ fb}$ which can be compared to the predicted Herwig++ cross section of $4.3 \pm 0.3 \text{ fb}$. The background-only hypothesis corresponds to a significance of 3.0. Limits on aQGC are obtained using event yields in the distribution of $p_T$ of the electron-muon pair for $p_T^{e\mu} > 120 \text{ GeV}$ and are visualised in Fig. 4. We can see that the limits are compatible with those by CMS and they are more stringent than those published by OPAL, D0 and CMS.

While studied in detail phenomenologically (see e.g.14–16), this analysis reports on finding first exclusive Higgs boson candidates at LHC experimentally. Event yields for the exclusive $H \rightarrow W^+W^- \rightarrow e^\pm \mu^\mp X$ were obtained from Fig. 4 right in the cut region and they amount to 6 for data, $0.023 \pm 0.003$ for signal and $3.0 \pm 0.8$ for background. The signal is obtained using KMR calculations which are based on gluon-induced production and the background is dominantly the exclusive $W^+W^-$ and inclusive $W^+W^-$ processes. These yields are then converted to the exclusive Higgs production cross-section using the CLs technique18 which gives $\sigma < 1.2 \text{ pb}$ at 95% CL (observed) and $\sigma < 0.7 \text{ pb}$ at 95% CL (expected). Since the cross-section for the exclusive Higgs production by KMR is about 3 fb, the observed upper limit is 400 times higher.

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**Fig. 4.** left) The observed log-likelihood 95% confidence-level contour and 1D limits for the case with a dipole form factor with $\Lambda_{\text{cut off}} = 500 \text{ GeV}$, right) distribution of transverse mass in the signal region of exclusive Higgs. The arrow denotes the selection. Taken from Ref.12.
5. Summary

In the analysis of diffractive dijets, ATLAS collaboration has measured rapidity gap and $\xi$ distributions in the presence of a hard scale. No gap plateau is observed and comparisons with predictions by Pythia 8.1 show that ND processes extend to very large gaps and small $\xi$ which eventually translates to no need for gap survival factor to describe the data. In the measurement of exclusive (photon-induced) events with the dilepton in the final state we confirm the necessity of absorptive corrections (20%) to calculations based on EPA. In the $W^+W^-$ final state we obtained an evidence for the $\gamma\gamma\rightarrow W^+W^-$ process, we improved limits on aQGC but have observed no excess and we also set first observed upper limits for the total cross-section of the exclusive Higgs production.

6. Acknowledgments

Supported by the project LG15052 and LM2015058 of the Ministry of Education of the Czech Republic.

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