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Referee's report on the doctoral thesis entitled: "Two-Photon Interactions in Proton-Proton Collisions with the ATLAS Experiment at the LHC" by Mateusz Dyndal

The thesis is devoted to the production of lepton pairs ($\mu^+\mu^-$ and e^+e^-) in proton-proton collisions at the LHC.
This thesis consists of three main parts:

- 1) Theoretical motivation,
- 2) Experimental tools,
- 3) The measurement,

It is further divided into 10 chapters where more specific topics are discussed.
The first part summarizes theoretical aspects of Standard Model and photon-photon interactions in proton-proton scattering. The author discusses those aspects of Quantum Electrodynamic and Quantum Chromodynamics which are related to the topic of his thesis. Chapter 1 contains fundamental aspects of underlying theory. Chapter 2 is more related to the content of the thesis. The author introduces the knowledge of electromagnetic form factors (Dirac and Pauli) of the proton. Next photon-photon creation of lepton pairs is discussed in more detail. The processes are classified into four categories, depending on whether protons undergo dissociation or stay intact. Basic QED formula for $\gamma\gamma \to l^+l^-$ reaction is given explicitly together with corresponding Feynman diagrams. Similar formulae for $\gamma\gamma \to W^+W^-$ are given too, which is not directly related to the present thesis. The so-called equivalent photon approximation is discussed. The author shows how fluxes of photons can be obtained from classical electromagnetic fields. Explicit expressions how to calculate fluxes in the impact parameter space are given. Section 2.3.3 is of special interest and is a part of original study of the author. Here an effect of absorption is discussed in the formalism formulated in the impact parameter space. Here absorption effects are related to the geometry of the collision, in particular the final size of the proton. I am not convinced that bounds $b_1 > r_p$ and $b_2 > r_p$ are necessary. They are usually not included e.g. in heavy ion ultraperipheral collisions and rather $|\vec{b}_1 - \vec{b}_2|$ is taken only. The author introduces the probability of no (inelastic) interaction between protons. Finally results for gap survival factor are presented in a two-dimensional space (x_1, x_2) and as a function of $W_{\gamma\gamma}$ i.e. also dilepton invariant mass, and of rapidity of dileptons y_{ll}. The author shows that the effect of absorption is not small, especially for large dileption invariant masses. This effect was usually neglected in the literature. In the momentum space approach
(see e.g. P. Lebiedowicz and A. Szczurek, "Exclusive production of heavy charged Higgs boson pairs in the $pp \to ppH^+H^-$ reaction at the LHC and a future circular collider", Phys. Rev. **D91** (2015) 095008.)
similar results can be obtained, among others the dependence of the gap survival factor on invariant mass of the produced central system. There t_1 and t_2 are crucial variables

for absorption. Similar dependence on M_{ll} was obtained there. Next proton dissociative reactions are discussed in a collinear approach and a formula for a flux factor is given. A consistent approach how to include photon to partons in the evolution equation is mentioned. In addition existing Monte Carlo codes (LPAIR, HERWIG++ and FPMC) are mentioned and their results are shown and compared in figures. There is interesting Fig.2.20 where pseudorapidity distribution of charged particles in double dissociation is shown in two different approaches (LPAIR vs PYTHIA 8). The two approaches give quite different results and its understanding is very important for future. The results obtained from LPAIR code depend on nucleon structure function used. The author compares in addition invariant mass distribution for the double dissociation in different approaches. In general, the double dissociative component is understood the least. The results of exclusive, single and double dissociative are compared with the Drell-Yan process. Clearly in the inclusive reaction the Drell-Yan mechanism dominates over the two-photon fusion one. This was demonstrated for several observables. Finally for completness the author compares cross sections for exclusive $\gamma\gamma$ process for e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ production. The bibligraphy of about 100 papers closes this part of the thesis. This part demonstrates that the author very well understands the underlying physics and can use different codes available on the market.

Second part of the thesis collects description of experimental infrastructure and tools related to the present thesis. This includes a general description of Large Hadron Collider, the ATLAS main detector, forward (existing and future) detectors as well as simulations of the so-called AFP detectors.

In chapter 3 the CERN accelerator complex is described. The main characteristics of the beam parameters are reviewed. The review of the ATLAS detector includes, inner detector, calorimeters, muon system as well as as ATLAS trigger system. The chapter discusses in addition the ATLAS simulation infrastructure, i.e. the whole simulation chain, detector simulation and so-called ATHENA software framework. This chapter is very general and is relevant for any PhD thesis related to the LHC.

Chapter 4 discusses existing forward detectors such as minimum bias trigger scintillators (MBTS), beam conditions monitor (BCM), LUCID Cherenkov detector, zero degree claorimeters (ZDC) and ALFA. A special attention is devoted to so-called AFP project which has a chance to be already partially realized during this year christmas shutdown. The analysis presented in the thesis does not not include measurement of protons, therefore it is not clear why the author does discuss the AFP detectors. This is not well explain in the thesis. Perhaps the author was engaged in the AFP project and this is an independent part of his thesis. I would be happy to hear an explanation. The section 4.2 disusses both the physics program related to AFP as well as many details related to the AFP detectors such as location, geometry, tracking and timing detectors. I understand that the AFP project and a similar project for CMS, are important ingredients allowing study of several interesting exclusive processes.

In chapter 5 a simulation of the AFP detectors is presented in detail. Here AFP silicon and timing detectors are considered. As explained in the thesis the author of the thesis contributed to the development of models for simulated event digitization and reconstruction. An explanation of this contribution during the public defense would be important to undersand the achievements of the author. This part of the thesis contains many technical details which supports the claim of the author. The bibliography to the chapter contains 69 positions.

The third part contains information about real experiment and presents results of the measurement. Many details of the data analysis concerning both $\mu^+\mu^-$ and e^+e^-

production are shown explicitly. The author explains how the data were selected. Tracks and vertices are important objects related to this issue. The values of the relevant cuts are given explicitly separately for $\mu^+\mu^-$ and e^+e^-. The selection of muons or electrons is discussed in detail. This part of the analysis is very professional and shows that the author controls all important ingredients.

Chapter 7 discussed event reconstruction, preselection of the data and background estimation. The autor presents analysis of data obtained at $\sqrt{s} = 7$ TeV collected in 2011 for total integrated luminosity of about 5 fb^{-1}. The signal of interest is exclusive production of dilepton pairs. Since the assumed cuts allow presence of different mechanisms Monte Carlo studies were performed to estimate the backgrounds and to understand the results of the measurements. The Monte Carlo studies include exlusive, single dissociative and double dissociative $\gamma\gamma$ processes, Drell-Yan processes, W^+W^- and $t\bar{t}$ production, etc. Different computer codes were used which requires good knowledge of the matter. Several corrections had to be included at this stage. Such problems like momentum scale and resolution, reconstruction efficiency, trigger efficiencies are important in this context. For control several observables such as distributions in M_{ll}, pseudorapidity of leptons, transverse momentum of the pair, acoplanarity for the preselected data were explained very well in terms of the sum of the Monte Carlo results for the different mechanisms. In my opinion the only mechanism which is not included in the studies is exclusive Drell-Yan mechanism discussed by our group (see
1) W. Schäfer, G. Ślipek and A. Szczurek, "Exclusive diffractive photoproduction of dileptons by timelike Compton scattering", Phys. Lett. **B688** (2010) 185,
2) G. Kubasiak and A. Szczurek, "Inclusive and exclusive diffractive production of dilepton pairs in proton-proton collisions at high energies", Phys. Rev. **D84** (2011) 014005.
).
There is, however, no Monte Carlo which includes this rather subtle mechanism. The size of the effect is, in my opinion, not negligible.

In chapter 8 the author analyses what happens when the purity of the exclusivity is increased by imposing cuts on lepton vertex separation, in acoplanarity and in transverse momentum of the lepton pair. The analysis relies on imposing a veto on charged-particle track multiplicity at the primary vertex and on the isolation from nearby pile-up induced vertices and tracks. To be precise, the final analysis assumes no additional tracks and vertices within longitudinal distance $\Delta z = \pm$ 3 mm from the lepton vertex. Clearly the condition of the veto improves purity of the $\gamma\gamma$ mechanisms. This is nicely demonstrated in Fig.8.1 where the result is explained by showing Monte Carlo results for different mechanisms separately. Again the sum of all mechanisms nicely describes the experimental results which gives confidence to the presented results. The figure demonstrates how the purity improves with the number of additional tracks attached to the dimuon or dielectron vertex. There is a detailed discussion on optimization of the veto region size. The crucial in this context is a dependence of significance on dimuon isolation distance cut. It is also discussed how exclusivity veto efficiency changes with the average number of pile-ups. To further improve the purity of the exclusive $\gamma\gamma$ contribution one imposes a maximal value of the transverse momentum of the dileption pair. The optimal value of 1.5 GeV was found in the optimization process. This condition suppresses the inclusive Drell-Yan component significantly. This is demonstrated for $p_{t,ll}$ and M_{ll} distributions.

The exclusive $\gamma\gamma \to l^+l^-$ contribution was extracted from the data by performing a binned maximum-likelihood fit to the dilepton acoplanarity distribution passing the other conditions. The fit contains two parameters. One is a multiplicative factor for the exclusive component related to not included explicity absorption effects. The found factor is about 0.8 (similar for electrons and muons) which is rather similar to the gap survival factor found in theoretical analysis of Dyndal and Schoeffel.

In chapter 9 the author tries to estimate statistical and systematic uncertainties and presents several cross-checks. The systematic uncertainties are related to lepton reconstruction and identification efficiency and effect due to pile-up description. Several figures illustrate the performed checks. The different contributions to the background are discussed once again. The photon emission from the leptons is considered here for the first time as it is important for precise understanding of acoplanarity distributions. When discussing templetes shapes the author presents an extra exponential factor in transverse momentum squared of the dileption pairs which is used to multiply the single-dissociative mechanism template. I see none theoretical explanation for such a factor. The author should discuss this issue during the public defense. In particular, I am interested how big this effect is on final results. The author discusses also the dependence on the details of electromagnetic form factors used in the calculation and finds 2 % "uncertainties". Table 9.4 summarizes sources of uncertainties for muon and electron pairs. Somewhat larger uncertainties are obtained for electron-positron pair production. It is not well explained to which final result (number) the uncertainty should be prescribed.

In chapter 10 the author collects cross sections for exclusive production of $\mu^+\mu^-$ and e^+e^- pairs in corresponding fiducial volumes. In addition, several control distributions are shown. Those distributions take into account cuts on dilepton acoplanarity. In these distributions, where all cuts have been imposed, the exclusive component constitutes more than 50 %. The author compares the ATLAS data with similar data obtained by the CMS collaboration. The measured values (both for ATLAS and CMS) are smaller than those obtained in EPA. Also the empirical factor multiplying the single dissociative component found from the fit is smaller than 1. However, this number is, in my opinion, not so precise as the size of the diffractive component sizeably depends on F_2 structure function used in the LPAIR calculation. This issue will be discussed in our paper, which is now in preparation. The lepton pair exclusive selection efficiency is shown in two figures. The quantity is, however, not clearly defined in the thesis.

Very short "Summary and conclusion" chapter closes the thesis. Here cross sections for exclusive component in fiducial volumes, different for $\mu^+\mu^-$ and e^+e^-, are given. The author stresses that the final results are consistent with the EPA results corrected by absorption effects. Finally the author reminds a possibility of a measurement of dilepton pairs using in addition forward protons by means of the AFP detectors discussed in the second part of the thesis. This would allow to understand the details even better. The bibligraphy (70 positions) closes the third part of the thesis.

In summary, the presented to me doctoral thesis is a good piece of work. It is written very well. I have found only some minor misprints. The author have demonstrated deep understanding of the considered processes and performed good quality analyses. In my opinion, the presented thesis fulfills all requirements necessary for the degree of doctor of physics and it is better than many other dissertation I have seen. Therefore I conclude that the candidate can take part in the official public defense. I leave the decision whether the dissertation should be rewarded to the last stage of the dissertation procedure.

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