arXiv:0807.1624v1 [hep-ph] 10 Jul 2008

As an Introduction: Quest for New Physics in Photon-Photon Interactions at the LHC[*]

Krzysztof Piotrzkowski[a†]

[a]Université catholique de Louvain, Center for Particle Physics and Phenomenology (CP3)
Chemin du Cyclotron 2, 1348 Louvain-la-Neuve, Belgium

A significant fraction of pp collisions at the LHC will involve (quasi-real) photon interactions occurring at energies well beyond the electroweak energy scale. Hence, the LHC can to some extend be considered as a high-energy photon-photon or photon-proton collider. This offers a unique possibility for novel and complementary research where the available effective luminosity is small, relative to parton-parton interactions, but it is compensated by better known initial conditions and usually simpler final states. This is in a way a method for approaching some of the issues to be addressed by the future lepton collider. Such studies of photon interactions are possible at the LHC, thanks to the striking experimental signatures of events involving photon exchanges, in particular the presence of very forward scattered protons.

Photon-induced processes, and in particular the two-photon production, have not been so far a subject of intense research at proton colliders. In 1973 the measurement of two-photon exclusive production of lepton pairs, $pp \to pl^+l^-p$, at the CERN Intersecting Storage Ring was proposed as means of a precise, absolute luminosity measurement [1]. It did not materialize then, since at the ISR energies it required detection of leptons at very small transverse momenta to obtain significant event statistics. Eventually, first such events have been observed at much higher energies, in $p\bar{p}$ collisions at Tevatron [2] and in ion-ion collisions at RHIC [3,4], with a little background and very striking signature – only two opposite charge tracks, identified as muons or electrons, without any other activity in the central detectors. Two tracks are back-to-back to an unusual degree, and have very little total transverse momentum. These two features are very characteristic of the two-photon production, due to the very small photon virtualities involved. On the one hand, it results in very forward scattering of incident protons, almost at zero-degree angle, on the other hand the dilepton system is produced by almost exact head-on collisions of quasi-real photons. Recently, the dilepton exclusive production in pp collisions has been proposed to measure absolute LHC luminosity [5,6,7]. This has been discussed also in the context of ion collisions at the LHC [8], as well as of new dedicated detectors capable to measure leptons at small transverse momenta [9]. Corrections due to the strong interactions have been studied in detail and were found to be negligible, therefore the QED calculation of the cross section should give sufficient accuracy [7]. These features make this process a perfect calibration candle for the two-photon processes at the LHC, and the CDF measurement can be regarded as a proof-of-principle experiment for photon physics at hadron colliders.

When the invariant mass of the system X produced in the two photon process, $pp \to pXp$ (see Fig. 1), is not too small, one can factorize the amplitudes for the two photon exchanges and for the photon interaction, $\gamma\gamma \to X$. This allows for introducing equivalent photon fluxes, which play similar role to the parton density functions for the hadron interactions. This is the basis of the Equivalent Photon Approximation (EPA), which allows the calculation of the proton cross-section

---

[*] *Contribution to Proceedings of the CERN workshop on High Energy Photon Collisions at the LHC, April 21-25, 2008.*

[†]Email: krzysztof.piotrzkowski@uclouvain.be

as a product of the photon cross-section and two equivalent photon fluxes [10]. Thanks to the huge center-of-mass energy at the LHC, $\sqrt{s} = 14$ TeV the photon fluxes are significant at large energies, well above 100 GeV, and drop with energy approximately like $1/x$, where $x = E_\gamma/E_p$ is the fraction of the incident proton energy carried by the exchanged photon.

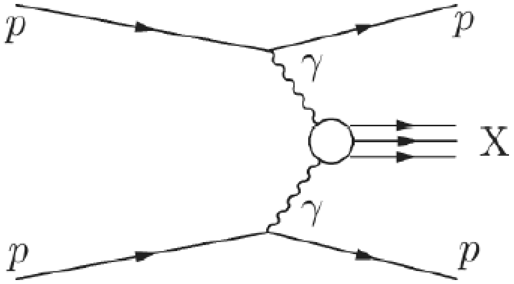

Figure 1. Generic diagram for the two-photon exclusive production, $pp \to pXp$, at the LHC. Two incoming protons are scattered quasi-elastically at very small angles, and the produced system X can be detected in the central detectors.

In elastic proton scattering, when the proton survives the photon exchange, the virtuality Q^2 of the exchanged photon is limited from below by a kinematical limit, $Q^2_{min} \approx M_p^2 x^2/(1-x)$, where M_p is the proton mass. The maximal photon virtuality is then due to the presence of the proton electromagnetic form factor, and of the finite spatial distribution of the proton charge, which cuts off completely the equivalent photon flux above $Q^2 = 1 - 2$ GeV^2. The photon flux drops with virtuality approximately like $1/Q^2$, therefore for small x the photon virtuality is on average very small, and one can usually treat these subprocesses as due to quasi-real photon collisions. This might be not true for inelastic production when at least one of the two incident protons dissociates into a low mass state[3]. Both minimal and maximal photon virtualities are much higher than for the elastic case at the same energy.

The photon-photon center-of-mass energy $W_{\gamma\gamma}$ is approximately given by $W^2_{\gamma\gamma} = x_1 x_2 s$, and assuming the EPA one can introduce the two-photon luminosity spectrum in $W_{\gamma\gamma}$, defined as a convolution of the two photon fluxes (integrated over Q^2) for fixed $W_{\gamma\gamma}$. Such a luminosity spectrum drops approximately like $1/W^2_{\gamma\gamma}$, and its inelastic part is about two times bigger than the elastic one [11]. By integrating the luminosity spectrum above some minimal center-of-mass energy, one can introduce the relative photon-photon luminosity $L_{\gamma\gamma}$. Effectively, $L_{\gamma\gamma}$ gives a fraction of the proton-proton luminosity which is available for $\gamma\gamma$ collisions, and is especially useful if a given photon-photon cross-section is approximately constant as a function of $W_{\gamma\gamma}$. For example, the elastic relative photon-photon luminosity at the LHC is equal to 1% for $W_0 = 23$ GeV (i.e. for $W_{\gamma\gamma} > 23$ GeV), and 0.1% for $W_0 = 225$ GeV [12]. Given the very large LHC luminosity, this leads to significant event rates of high-energy processes with relatively small photon-photon cross sections.

This is even more true for the photon-proton interactions at the LHC, where both energy reach and effective luminosities are much higher than for the photon-photon case [13]. The high luminosity and the high c.m.s. energy of photoproduction processes offer interesting possibilities for the study of electroweak interaction and for searches beyond the Standard Model (SM) up to TeV scale. For example, one can extend studies at HERA of the single W boson photoproduction, or of the searches of anomalous Flavor Changing Neutral Current top quark couplings, to much higher energies [12], effectively converting the LHC into a super-HERA collider for this class of processes. Some of the photoproduction cross-section are so large that become a significant part of the total inclusive cross-section at the LHC. For example, the associated photoproduction of WH is about 5% of the total inclusive

---

[3] One can consider also quarks as sources of the photons, but this involves yet higher photon virtualities, resulting in much smaller equivalent fluxes. In addition, the striking signature of lack of the proton remnants in the central detectors is then missing.

cross-section for $pp \to WHX$ at the LHC [12]!

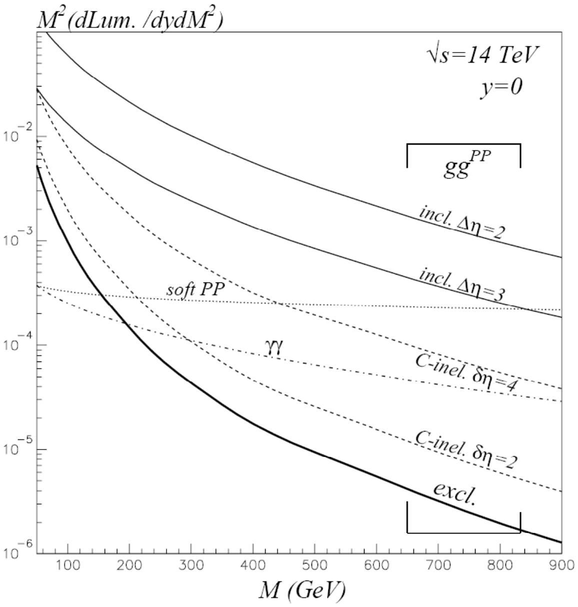

Figure 2. Luminosity spectra including suppression due to the rescattering, for the exclusive photon-photon collisions (dashed-dotted line) and for the central exclusive diffraction (solid line) at central rapidity ($y = 0$) at the LHC [14]; M is the invariant mass of the centrally produced system X. Other curves show the corresponding spectra for the inclusive diffraction.

One needs however to consider corrections beyond the EPA due to a possibility of strong interactions between protons, or the so-called rescattering effects. The resulting suppression, or the non 100% probability of proton survival, of the cross sections weakly depends on the invariant mass of the exclusively produced state X. For the production of pairs of massive particles, as $pp \to pWWp$, the proton survival probability is estimated to be about 85% [14]. In photoproduction, the proton survival probability is still high, though in general is slightly lower than in the photon-photon case. For example, it is about 70% for the single W boson photoproduction [15]. In fact, the measurements of photon-induced processes were proposed for verification of the models describing such soft, non-perturbative strong interactions, which occur at large impact parameter in pp collisions [15].

In addition, one should discuss the potentially dangerous background due to the central exclusive diffraction (CED). In Fig. 2, the elastic photon-photon luminosity is compared to the luminosity of the CED, both including the proton survival probability [14]. The proton survival probability is in general much smaller in diffraction due to smaller impact parameters involved, or in other words due to smaller range of gluon exchanges with respect to the photon ones. Plots in Fig. 2 show that for the invariant masses of the produced system above 200 GeV the $\gamma\gamma$ luminosity takes over, so the systems exclusively produced at the LHC and of the largest invariant mass are due to photon-induced interactions. It means also that the CED is heavily suppressed for production of massive non strongly-interacting particles and can be safely neglected. For example, the gluon mediated exclusive production of W boson pairs, is about 100 times smaller than the two-photon production at the LHC [16].

In general, the exclusive two-photon production, $pp \to pXp$, provides clean experimental conditions, and well defined final states can be then selected, and precisely reconstructed. Moreover, detection of the final state protons, scattered at almost zero-degree angle, in the dedicated very forward detectors (VFDs), provides another striking signature, effective also at high luminosity and with large event pile-up [11,17]. A set of VFDs at 220 m or 420 m from the LHC interaction points will be capable of tagging photon interactions within the wide photon energy range of 20 GeV $< E_\gamma <$ 900 GeV [18]. In addition, the photon energies can be then well measured with 1–5% relative resolution and used for the event kinematics reconstruction [11,17,18]. The transverse momenta of the scattered protons, or equivalently the photon virtualities, are more difficult to measure, but providing the high resolution VFDs and precise detector alignment the absolute p_T resolution of about 0.3 GeV/c could be achieved [18]. This then allows for some additional control of the diffractive background, which in general results in proton scattering at larger p_T [6]. As was mentioned, the photon tagging allow to suppress very effectively, the inclusive backgrounds, in particular it is true for double tagging of the exclusive two-photon processes, which is equivalent to a triple coincidence – the detection in the same beam crossing of the system X in the central detectors and of two protons scattered in opposite directions. This technique should be effective even at the highest LHC luminosity [17]. In addition, special picosecond resolution time-of-flight detectors are proposed to provide yet another, direct control and suppression of the backgrounds due to accidental coincidences [17]. This is based on measuring the longitudinal position of event vertex using the *z-by-timing* technique, and comparing it with the event vertex z-position as determined by the central detectors[4]. Finally, measurements of the forward proton scattering angles provide offers also a unique possibility for determination of the CP parity of the produced system X by measuring the azimuthal asymmetry of the outgoing protons, especially interesting in case of observation of new states, beyond the SM [20].

In the center of interest in the high energy two-photon interactions at the LHC lies, very naturally, the exclusive production of non strongly-interacting pairs of charged particles. It has been proposed as a possible, novel and original way of detecting supersymmetric charginos, sleptons and the charged Higgs bosons [21]. But is is also an excellent test-ground for the SM, in particular in the case of the two-photon W boson pair production [22,23]. Detection of new, massive and quasi-stable charged particles, as predicted in some variants of supersymmetry [24], is very unambiguos in two-photon exclusive production, allowing for clear interpretation. Assuming the possibility of measuring such events at the highest luminosity and negligible backgrounds, this type of search for new states could reach sensitivity to very interesting masses up to 250–300 GeV.

Finally, photon physics can be studied also in ion collisions at the LHC, where the lower ion luminosities are largely compensated by the high photon fluxes due to the Z^2 enhancement (for each nucleus), where Z is the ion charge. For example, the two-photon exclusive production of the SM Higgs boson in ion collisions was considered as a discovery channel for a very light H [25]. However, for the mass of the exclusively produced system above 100 GeV, the coherent enhancement is not effective – the exchanged photons prefer to couple to protons in an ion rather than to the total ion charge Z. It means that at the not too high energy, where the strong electromagnetic enhancement is still effective one can profit from an improved significantly signal-to-background ratio. This allows for studies of wide range of processes and new phenomena, involving in particular high parton density, nuclear and strong field effects [26]. Finally, it is worth adding, that in ion collisions, though in more limited range, the proton (and/or neutron) forward tagging technique can also be applied at the LHC.

In summary, the photon-induced processes offer a rich and exciting field of research at the LHC. It shoud provide complementary and interesting results for tests of the Standard Model as well as for search of New Physics. One cannot afford to miss it – on the contrary, dedicated forward detectors should be installed if one wants to get out the best of the LHC.

Acknowledgments

The author thanks D. d'Enterria for a careful reading of the manuscript and useful comments.

REFERENCES

1. V.M. Budnev, I.F. Ginzburg, G.V. Meledin and V.G. Serbo, Nucl. Phys. B **63** (1973) 519.
2. A. Abulencia *et al.*, Phys. Rev. Lett. **98**, (2007) 112001.

---

[4] It should be noted that for the two-photon events this can be done using the time difference of the two forward scattered protons. For photoproduction it requires a very good timing for central detectors. As was shown in Ref. [19], for example, a 100 ps timing resolution of the central calorimeters would bring significant suppression of accidental overlay events.

3. J. Adams *et al.* [STAR Collaboration], Phys. Rev. C **70**, 031902 (2004) [arXiv:nucl-ex/0404012].
4. D. G. d'Enterria, *Coherent photoproduction of J/ψ and high-mass e^+e^- pairs in ultra-peripheral AuAu collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, arXiv:nucl-ex/0601001.
5. A.G. Shamov and V. I. Telnov, Nucl. Instrum. Meth. A **494** (2002) 51.
6. K. Piotrzkowski, *Proposal for Luminosity Measurement at LHC. ATLAS note* PHYS–96–077 (1996), unpublished; ATLAS Collaboration, *Detector and Physics Performance. Technical Design Report*, CERN/LHCC/99–14 TDR 14, (1999).
7. V. A. Khoze, A. D. Martin, R. Orava and M. G. Ryskin, Eur. Phys. J. C **19** (2001) 313.
8. D. Bocian and K. Piotrzkowski, Acta Phys. Polon. B **35** (2004) 2417.
9. M.W. Krasny, Nucl. Instrum. Meth., A **584**, (2008) 42.
10. V. M. Budnev *et al.*, Phys. Rept. **15** (1974) 181.
11. K. Piotrzkowski, Phys. Rev. D **63** (2001) 071502.
12. J. de Favereau *et al.*, *High energy photon interactions at the LHC*, CP3–08–04, June 2008, to be submitted to EPJC.
13. K. Piotrzkowski, *High energy photon interactions at the LHC*, Proceedings of DIS 2005, Madison, Wisconsin, published in AIP Conf. Proc. **792** (2005) 544; T. Pierzchała and K. Piotrzkowski, Proceedings of DIS 2006, Tsukuba, published in *Tsukuba 2006, Deep inelastic scattering* 341.
14. V. A. Khoze *et al.*, Eur. Phys. J. C **23** (2002) 311; private communication from V. Khoze.
15. V. A. Khoze, A. D. Martin and M. G. Ryskin, Eur. Phys. J. C **24** (2002)459.
16. B. E. Cox *et al.*, Eur. Phys. J. C **45** (2006) 401.
17. M. Albrow *et al.*, *The FP420 R&D Project: Higgs and New Physics with forward protons at the LHC FP420*, arXiv:0806.0302 [hep-ex].
18. J. de Favereau de Jeneret, X. Rouby and K. Piotrzkowski, JINST **2**: P09005 (2007), arXiv:0707.1198v1 [physics.acc-ph] (CP3–07–13).
19. S. N. White, *On the correlation of subevents in the ATLAS and CMS/Totem experiments*, July 2007, arXiv:0707.1500 [hep-ex].
20. V. A. Khoze, A. D. Martin and M. G. Ryskin, Eur. Phys. J. C **34** (2004) 327; V. A. Khoze, A. D. Martin and M. G. Ryskin, Eur. Phys. J. C**14** (2000) 525; V. A. Khoze, A. D. Martin and M. G. Ryskin, Eur. Phys. J. C **24** (2002) 581.
21. J. Ohnemus, T Walsh and P. Zerwas, Phys. Lett. B **328** (1994) 369.
22. T. Pierzchała, *High Energy Photon-Photon Interaction at the LHC*, submitted to the proceedings of the Photon 2007 Conference, CP3–07–33 (2007).
23. M. Boonekamp, C. Royon, J. Cammin and Robert B. Peschanski, Phys. Lett. B **654** (2007) 104.
24. M. Ibe, R. Kitano, JHEP 0708 (2007) 16.
25. E. Papageorgiu, Phys. Lett. B **352** (1995) 394.
26. A. Baltz et al., Phys. Rept. **458** (2008) 1.