# BACKGROUND TO HIGGS-BOSON SEARCHES FROM INTERNAL CONVERSIONS OF OFF-SHELL PHOTONS ASSOCIATED WITH $Z/\gamma^*$-BOSON PRODUCTION AT THE LHC* **

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This paper presents the studies of the background contribution to the $H \to 4l$ searches originating from the processes of off-shell (virtual) photon emissions and their conversions into lepton pairs accompanying the production of $Z/\gamma^*$-bosons at the LHC. They extend the analyses of the irreducible background presented in the ATLAS and CMS Higgs papers [*Phys. Lett.* **B716**, 1 (2012); *Phys. Lett.* **B726**, 88 (2013); *Phys. Rev.* **D90**, 052004 (2014); CERN-PH-EP-2014-170, to appear in *Phys. Rev.* **D**; *Phys. Lett.* **B716**, 30 (2012); *Phys. Rev.* **D89**, 92007 (2014)] by taking into account the emissions of off-shell photons by parton showers. Including these effects does not change significantly the Higgs-searches background level, provided that the transverse momentum of each of the final-state leptons is restricted to the range of $p_{\mathrm{T},l} > 7$ GeV. In the kinematical region extended towards

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lower lepton transverse momenta, the parton-shower contribution becomes important. A measurement method for pinning down the parton-shower effects has been proposed.

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## 1. Introduction

The Higgs boson discovery [1, 2] is the first out of all the pivotal *experimental* particle physics discoveries which relies, to such a large extent, on the *theoretical* calculations of the Standard Model (SM) background.

Given its importance for the future experimental program in high energy physics, it should be of utmost interest to keep exposing the theoretical background calculations to a broad spectrum of experimental and theoretical stress tests, no matter how widely this discovery is acclaimed.

Majority of the SM background processes leading to Higgs-like signatures have already been identified and extensively studied experimentally, using the data extrapolation driven techniques, and theoretically, using the existing Monte Carlo generators of SM processes. The basic two questions which have motivated our studies presented in this and in two other papers [3, 4] are:

1. Is the list of the background sources complete?
2. Are various approximations inherent in the Monte Carlo generators, used in the determination of the experimentally irreducible background, controlled to the claimed precision?

In our previous work [3], see also [4], we have concentrated our attention on the double Drell–Yan process (DDYP), considered to be negligible in the ATLAS and CMS analyses. We have demonstrated, using a simplified model of DDYP, the appearance of a peak in the four-lepton invariant mass, $m_{4l}$, distribution which mimics the 125 GeV Higgs signal in its $H \to ZZ^*$ decay channel. This "Higgs-like" peak is generated by the interplay of a steeply falling $m_{4l}$ distribution and the kinematical threshold effect driven by the experimental cuts on the outgoing leptons variables. The cuts influencing the background peak position are similar in the ATLAS and CMS analyses and are, therefore, reflected in similar peak positions within a 2 GeV interval. The coincidence of the Higgs peak and the DDYP peak could be accidental. It is, however, remarkable that once the absolute normalisation of the DDYP contribution is fixed using the LHC $W^+W^-$ cross section data [4], the DDYP process could provide an alternative explanation of the Higgs-like excesses of the events both in the $H \to ZZ^*$ and in the $H \to WW^*$ channels.

The claim of the ATLAS and CMS collaborations that DDYP can be neglected as a potentially alarming source of background was based on the assumption of uncorrelated: (1) longitudinal momentum, (2) transverse position, (3) flavour, (4) charge and (5) spin of the partons taking part in DDYP, and on the assumption of the process independent value of $\sigma_{\rm eff}$, governing the strength of double-parton scattering (DPS) processes [1, 2]. The above, in our view unjustified, assumptions lead to a significant underestimation of the contribution of DDYP to the Higgs searches background. As we argued in [3], its contribution must be, given the lack of the adequate theoretical calculations, determined experimentally, *e.g.* by using experimental methods proposed therein and in [5].

In the current paper, we study another potentially important contribution to the Higgs searches background, which has not been entirely taken into account in the ATLAS and CMS papers [1, 2], namely the processes of emission and subsequent internal conversion of off-shell (virtual) photons radiated by quarks and leptons participating in the production and leptonic decays of $Z/\gamma^*$ bosons. Examples of the Feynman diagrams corresponding to these processes are shown in Fig. 1.

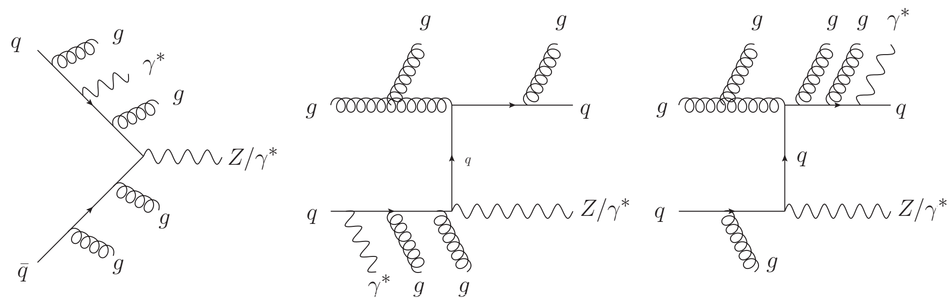


Fig. 1. Some examples of the parton-shower diagrams for the inclusive $Z/\gamma^*$ production processes contributing to the Higgs searches background. The final-state leptons are produced by the decays of the $Z/\gamma^*$ boson and by the internal conversions of virtual photons, $\gamma^*$. The virtual photons can be emitted at an arbitrary stage of the parton shower.

The Matrix Element (ME) contribution to these processes — for the case of *quark–antiquark annihilations* — was considered in the ATLAS and the CMS analyses [1, 2], and evaluated using the POWHEG-BOX/ZZ next-to-leading-order (NLO) ME generator (POWHEG) [6]. The POWHEG quark–antiquark annihilation contribution to the Higgs searches background in $ZZ^*$ channel was found to be the dominant one [1, 2].

The *first* question which, in our view, must be addressed is if the contribution of the *quark–gluon scattering processes* can be neglected. These processes are suppressed by an $\mathcal{O}(\alpha_s)$ factor. However, this suppression may be to a great extent neutralised by a large value of the ratio of the gluon to quark parton distribution functions (PDFs) in the $x$-domain which is pertinent to the Higgs signal extraction. The lowest-order quark–antiquark and the quark–gluon scattering diagrams for $Z/\gamma^*$ pair production are shown in Fig. 2.

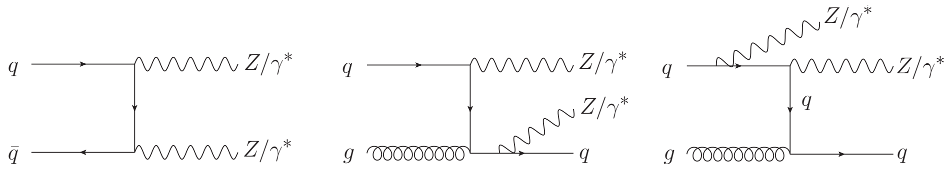


Fig. 2. The lowest-order matrix element (ME) contributions to the processes of $Z/\gamma^*$ pair production in quark–antiquark and quark–gluon scattering.

The *second* question is whether the contribution of processes in which virtual photons are emitted by *parton showers* (PS), both for the quark–antiquark and quark–gluon collisions, can be neglected for the inclusive four-lepton analysis[1]. The strength of this contribution increases with decreasing off-shellness of virtual photons proportionally to $\ln^2(\hat{s}/m^2_{\gamma^*})$, where $\hat{s}$ is the invariant mass of the four-lepton system and $m_{\gamma^*}$ is the virtual photon mass [7].

In this paper, we address the latter question, while the former one will be addressed in a separate publication [8].

The "PS" question cannot, at present, be answered at NLO precision, because an appropriate NLO Monte Carlo generator producing interleaved QED and QCD parton showers, including the full set of the re-summed $\alpha^2_{\rm QED}$ corrections to the inclusive production of vector bosons, does not exist. The studies presented in this paper are based on the leading-order (LO) PYTHIA 8 event generator [9], which has inferior quality with respect to POWHEG in calculating the NLO ME contribution to the four-lepton final state. However, virtual photon emissions by the initial and final state quarks and leptons are included in all stages of the QCD/QED-interleaved parton shower.

The PYTHIA PS description of the virtual photon emissions has never, to our best knowledge, been tested in the kinematical domain discussed in this paper. Therefore, an evaluation of its precision is the prerequisite for its subsequent use in the studies of the Higgs searches background. Such an

[1] In the fully inclusive searches, both the number of lepton pairs and the four-lepton phase space are not restricted.

evaluation is presented in Section 3, following the introductory discussion of the background sources to the Higgs searches in the four-lepton channel. This discussion is presented in Section 2. In Section 4, the results of our calculations are presented. The proposal of an experimental test aiming to verify the importance of the QED/QCD PS contribution to the Higgs-boson searches background is discussed in Section 5.

## 2. $H \to 4l$ background sources

The dominant *irreducible background* contribution to the Higgs boson searches in the $H \to ZZ^* \to 4l$ decay channel arises from the direct production of $(Z_1, Z_2)$ pairs [1, 2]. Throughout this paper, we shall use the term $Z_1$ for the opposite sign and the same flavour lepton pair with its invariant mass higher or equal 50 GeV, and the term $Z_2$ for the pairs with in the remaining mass region. These terms are in close relation to those defined in [2], where they represent, respectively, higher and lower invariant mass pairs. In the $m_{4l}$ region where the Higgs signal was reported, both definitions can be considered as equivalent because the remaining contributions of the $(Z_1, Z_1)$ and $(Z_2, Z_2)$ pairs to four-lepton events are negligible[2].

At the LHC, the $(Z_1, Z_2)$ pairs are produced in quark–antiquark annihilations, quark–gluon scattering and gluon–gluon fusions. In this paper, we focus our attention on the first two contributions.

The amplitude level mechanism of the $(Z_1, Z_2)$ pair production can be represented as the Drell–Yan production of $Z/\gamma^*$ accompanied by the initial or final state radiation of $\gamma^*$, followed by its conversion into the opposite charge and the same flavour lepton pair[3]. The off-shell photons can be radiated both by the final state leptons coming from the $Z$-boson decays, and by the initial and (in the case of the quark–gluon processes) final state quarks. At the cross section level, their origin cannot be unambiguously identified and the corresponding interference terms as well as the interference terms arising, in the case of the $4\mu$ and $4e$ final states, from the presence of indistinguishable fermions must, in principle, be taken into account. However, for the Higgs boson mass region discussed in this paper, the interference effects are expected to be small [6].

In the ATLAS and CMS papers [1, 2], the irreducible background to the $H \to 4l$ decay channel is claimed to be controlled, for the quark–antiquark annihilation contribution, within 3–10% accuracy. This uncertainty was estimated by varying the factorisation and renormalisation scales, and by

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[2] No $(Z_2, Z_2)$ events and one $(Z_1, Z_1)$ event have been found in the mass region 120–130 GeV in full the samples of the ATLAS and CMS collected data [1, 2].

[3] There can be also radiation/conversion of $Z^*$, but its contribution to the $Z_2$ mass region is negligible.

varying PDFs within their uncertainty range. The missing contribution of the quark–gluon scattering processes and the missing PS contribution were not accounted for in the quoted above accuracy estimation.

The event generator which was used in [1, 2] for the determination of the quark–antiquark annihilation background and its uncertainty was POWHEG [6]. This ME generator does not cover entirely the phase space of virtual photon emissions, in particular the region populated by virtual photons emitted at the "early stage" of the PS development. As long as the region of $m_{Z_2} < 20$ GeV is avoided in the Higgs searches, such an approximation is claimed to be justified [6]. For the searches reported in [1, 2], which open the phase space towards smaller masses, the validity of such a statement remains to be verified.

The effect of the two approximations made in [1, 2]: (1) the missing contribution of the quark–gluon processes and (2) the missing PS contribution, even if expected to be small, and consequently not taken into account in the ATLAS and CMS analyses, needs to be estimated to gain a full confidence in the claimed precision of the irreducible background level.

It remains to be mentioned that the contribution of the quark–gluon scattering processes in which virtual photons are emitted in PS initiated by the final-state recoil quark may also influence the size of the *reducible background* contribution. The reducible background [1, 2] is dominated by $Z +$ jets events (mostly $Zb\bar{b}$ and $t\bar{t}$) which give rise to the detector reconstructed objects faking the isolated lepton identification signatures. This background is detector and analysis method dependent. Its size was estimated using data driven methods [1, 2]. In general, these methods define control regions to monitor the background level and subsequently extrapolate its magnitude to the signal region, based on the assumption that the $Zb\bar{b}$ and $t\bar{t}$ events are the sole background sources.

The processes of radiation of virtual photons by the outgoing quarks (so far not taken into account in the ATLAS and CMS analyses) produce isolated leptons already in the "$Z$ plus a single light-flavour jet" events, as long as $m_{Z_2}$ is large enough to sweep out the leptons outside of the recoil quark jet cone. Inclusion of such a process could influence the shapes of the lepton track's "Distance of the Closest Approach" (DCA) and the lepton candidate isolation criteria, leading to an underestimation of the reducible background level. This effect is expected to be significantly amplified in the kinematical region selected for the Higgs bosons searches in which $m_{Z_2} > m_b$, where $m_b$ is the mass of the $b$-quark. It has to be mentioned that the processes of radiation of large mass virtual photons are not generated by the standard versions of the PS generators used by the LHC experiments.

## 3. PYTHIA precision

The fully inclusive $Z/\gamma^*$ processes, including both the quark–antiquark and quark–gluon collisions, were generated for 8 TeV proton–proton collisions using PYTHIA 8.180. Only the leptonic decays were retained. The minimal mass of the $Z/\gamma^*$ boson was set to be 50 GeV. The minimal transverse momentum cut-off of virtual photons was equalised for the quark and lepton emissions to be 0.1 GeV for time-like showers and 0.01 GeV for space-like showers. Both cuts are significantly lower than the invariant masses of the virtual photons studied in this paper, $m_{\gamma^*} > 5$ GeV. The phase space for the generated virtual photon masses up to the value of $m_{\gamma^*} = 50$ GeV was open. Hadronisation processes, except for prompt decays, were switched off, and the default CTEQ 5L PDFs [10] were used.

For the calibration of the PYTHIA generator precision in describing the processes of large-mass virtual photon emissions by parton showers, we analyse first its performance for the processes of $Z$-boson decays into four leptons, $Z \to 2l + \gamma^* \to 4l$. Technically, we select the region of 80 GeV $< m_{4l} <$ 100 GeV where, for $m_{\gamma^*} > 5$ GeV, a large majority (more than 97%) of virtual photons are emitted by the leptons coming from the $Z$-boson decays. This *calibration* region is particularly well suited for testing how precisely the PYTHIA PS recoil model mimics the exact ME calculations.

Throughout this paper, the term lepton represents the *dressed* lepton. For PYTHIA, where the PS emissions of virtual photons are interleaved with the emissions of on-shell photons, the origin of the latter was traced back to the mother leptons and their four-momenta were added to the four-momenta of the mother leptons to form dressed leptons[4].

The departure point of our analysis is the comparison of the shapes of the distributions obtained with PYTHIA and POWHEG.

The $ZZ$ pair production events of POWHEG-BOX version 2129 were generated and analysed in our studies. We took into account the full set of the NLO ME processes leading to the production of four charged leptons, including both the quark–antiquark and quark–gluon collisions. In order to study the magnitude of the interference effects, two samples of events were generated, including and excluding the interference effects. For the minimum mass of the lepton pairs coming from the $Z/\gamma^*$ decays, we required $m_{ll} > 5$ GeV. Since in POWHEG the QED radiation processes are not taken into account, its final-state leptons are, by definition, the *dressed* leptons. The MSTW2008nlo68cl parametrisation [11] of the PDFs was used in the event generation.

[4] The inclusion of virtual photons in the dressing procedure can be neglected for the specified above cut-off values of the minimal transverse momentum of the virtual photons.

In this paper, PYTHIA and POWHEG event generation is restricted to the $4\mu$ final state. Their extension to an arbitrary flavour mixture of the lepton pairs is straightforward. The choice of the $4\mu$ final state maximises: (1) the interference effects related to the presence of indistinguishable fermions in the final state, and (2) the effects caused by misassociation of the leptons to their respective $Z/\gamma^*$ and $\gamma^*$ parents. The magnitude of the interference and misassociation, determined with such a sub-sample of events, provides an upper limit of these effects for an arbitrary flavour composition of the four-lepton final state.

In Fig. 3, we show the distributions of the mass, $m_{Z_2}$, and transverse momentum, $p_{\mathrm{T},Z_2}$, of the $Z_2$ lepton pairs for PYTHIA and POWHEG and the ratio of their $m_{Z_2}$ distributions. The interference effects in POWHEG are neglected for these plots. In the generated sample of events, the transverse momentum of each of the leptons satisfies the condition $p_{\mathrm{T},l} > 4$ GeV, representing roughly the lower limit of the ATLAS and CMS isolated lepton detection and reconstruction acceptance. In all the plots shown in Fig. 3, $Z_2$ represents the pair of the opposite charge leptons remaining after selection of the leading $Z_1$ pair. The leading $Z_1$ pair is chosen as the one having its reconstructed mass closest to the $Z$-boson mass.

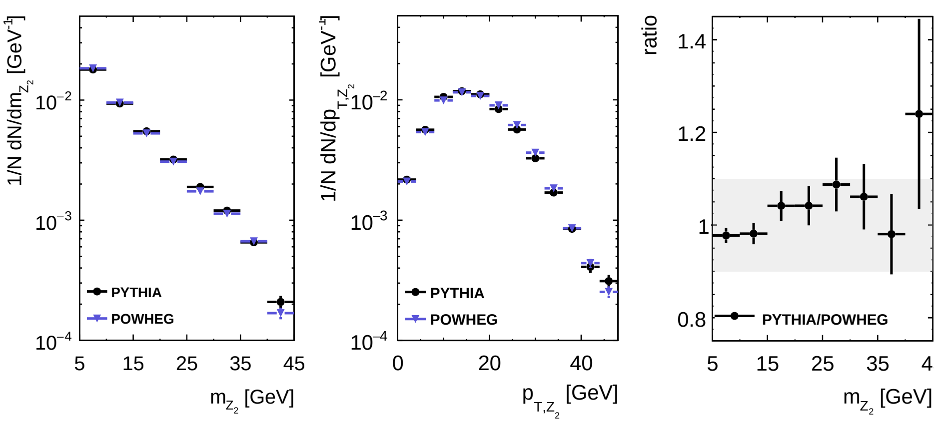


Fig. 3. The comparison of the distributions of the invariant mass $m_{Z_2}$ (left) and the transverse momentum $p_{\mathrm{T},Z_2}$ (middle) of virtual photons in the $Z$-resonance region 80 GeV $< m_{4l} <$ 100 GeV for PYTHIA and POWHEG. The POWHEG interference effects are neglected in this comparison. Only $4\mu$ events satisfying the: (1) $m_{Z_2} > 5$ GeV and (2) $p_{\mathrm{T},l} > 4$ GeV conditions contribute to these plots. The right plot shows the ratio of the $m_{Z_2}$ distributions for PYTHIA and POWHEG.

We find an unexpectedly good agreement of the PYTHIA and POWHEG distributions over the full range of the $Z_2$ pairs masses and over the full range of their transverse momenta. It has to be reminded here that PYTHIA uses the parton shower approximations in the extended virtual photon phase-space region, up to the invariant mass of of 50 GeV — the region where such approximations have never been tested.

In general, and particularly in the $Z$-resonance region of 80 GeV $< m_{4l} <$ 100 GeV, the association of the leptons to the $Z_1$ and $Z_2$ pairs may not reflect their amplitude-level association to the $Z/\gamma^*$ and $\gamma^*$. Assuming, for a while, the absence of the interference terms, the effect of such an algorithmic misassociation can be determined using the PYTHIA sample of events because there each lepton can be traced back to its mother particle. In the left panel of Fig. 4, the resulting misassociation bias is represented as the difference between the $m_{Z_2}$ distributions: (1) for the $Z_2$ pairs found algorithmically and (2) for the $Z_2$ pairs coming from conversions of virtual photons emitted by leptons and quarks.

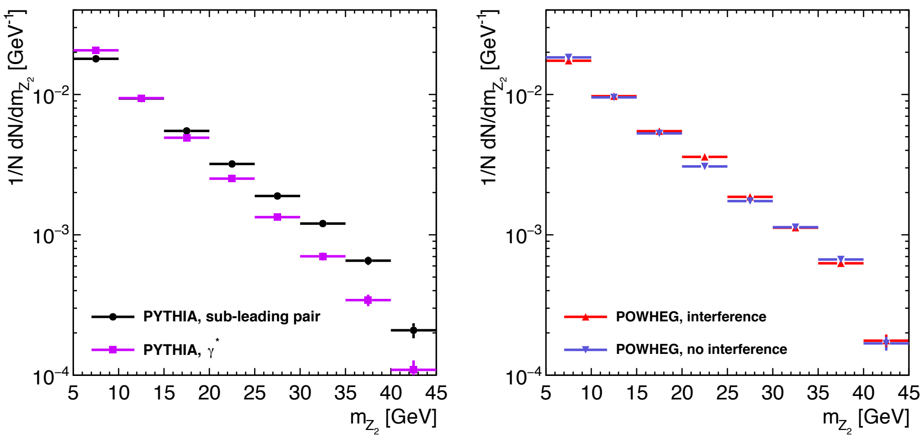


Fig. 4. (Left) The comparison of the PYTHIA distributions of the invariant mass $m_{Z_2}$: (1) for the $Z_2$ pairs found algorithmically, and (2) for $Z_2$ the pairs coming from conversions of virtual photon emitted by leptons and quarks. (Right) The comparison of the POWHEG distributions of the invariant mass $m_{Z_2}$: (1) including and (2) excluding the interference effects.

The predicted PYTHIA distributions, prior to any comparison with the data, must be corrected for the missing interference effects. The corrections are determined using POWHEG by taking the ratio of the distributions obtained by including (excluding) the interference effects. The size of the interference corrections to the $m_{Z_2}$ distribution is illustrated in the right panel of Fig. 4 where POWHEG distributions are shown twice, including and excluding the interference effects. Since the interference effects are absent for the $Z \to 2\mu 2e$ decays, the plotted differences for the $Z \to 4\mu$ channel are larger than those for the all-flavour inclusive background to Higgs searches.

It is interesting to note that the misassociation effects are significantly larger than the interference effects. They have never been studied before because the logic of the POWHEG generator forbids tracking back the final leptons to their amplitude-level origin. The size of the misassociation effects underlines the necessity of using precisely the same pair-association algorithm for data and for Monte Carlo samples of events. In the following, we shall use only the algorithmic association of leptons to the $Z_1$ and $Z_2$ pairs, defined in Section 3.

Since PYTHIA is a LO-type generator, it is necessary to apply a $K$-factor to match the absolute normalization of cross sections. We exploit the ATLAS $Z \to 4l$ data [12] to determine the $K$-factor for subsequent studies. The ATLAS experiment measured the total $Z \to 4l$ cross section in the $Z$-boson resonance peak, 80 GeV $< m_{4l} <$ 100 GeV, requiring the minimal mass of muon or electron pairs $m_{l^+l^-} > 5$ GeV, to be $\sigma^{\rm data}_{Z\to 4l} = 107 \pm 9\,({\rm stat.}) \pm 4\,({\rm syst.}) \pm 3\,({\rm lumi.})$ fb. The corresponding cross section calculated with PYTHIA is $\sigma^{\rm PYTHIA:LO}_{Z\to 4l} = 89$ fb. In the following, we shall thus apply the $K$-factor of 1.2 to all the cross section calculations.

Assuming POWHEG to be the precision template for our studies, we conclude the discussion presented in this section by the statement that the processes of emission of virtual photons from the outgoing leptons are controlled by the PYTHIA generator with a precision better than $\sim 10\%$. This defines the precision level of the studies presented in the next section.

## 4. Background calculation results

Having analyzed the precision of the PYTHIA model of the emission of large-mass virtual photons from the final state leptons, we focus now our attention on the processes in which the virtual photons are emitted not only by the final-state leptons but, predominantly, by the PS processes initiated by quarks and gluons.

The extension of the "leptonic calibration" of the PYTHIA precision to quark radiation processes is based on the assumption that the strength of the QCD confinement forces and the precise values of the quark masses, which, in principle, may lead to significant differences in photon emissions by leptons and quarks, become irrelevant for the process of highly virtual, $m_{\gamma^*} \gg m_e, m_q, \Lambda_{\rm QCD}$, photon emissions. Assuming its validity, quarks, except for the differences in the electric charges, can be considered as equivalent emitters of highly virtual photons as leptons. Consequently, the control of the PYTHIA precision, estimated using virtual photon emission by leptons, can be extended to processes involving quarks.

In the four-lepton invariant mass region of 100 GeV $< m_{4l} < 2m_Z$, the dominant process producing four-lepton final state is the radiation of virtual photons from the initial and final state quarks involved in the Drell–Yan production of $Z/\gamma^*$. The processes of leptonic radiation of virtual photons contribute at $< 10\%$ level, populating mainly in the region of masses close to the lower boundary of this mass region[5].

The results presented in this section are based on the PYTHIA sample of $Z/\gamma^*$ Drell–Yan events generated in the region of $m_{Z/\gamma^*} > 50$ GeV. Both leptons and (PS) quarks participating in the $Z/\gamma^*$-boson production process are allowed to radiate virtual photons, provided that their invariant mass is below 50 GeV. For the virtual photon radiation from the quarks, the $Z_1$ boson is thus *always* associated with the $Z/\gamma^*$-boson matrix element, while the $Z_2$ boson is *always* generated by the PYTHIA parton showers. To take into account a reverse and symmetric configuration which is not generated, all events where the origin of $Z_2$ is traced back to a quark acquire the weight equal to 2. A fraction of the $4l$ phase space remains, however, uncovered in such a simplified event generation procedure. The missing events not taken into account in the PYTHIA generation process, which may potentially contribute to the background to the Higgs searches, contain the $(Z_1, Z_1)$ and $(Z_2, Z_2)$ pairs. Their contribution to the background under the Higgs peak, 120 GeV $< m_{4l} <$ 130 GeV, calculated using POWHEG, is below 1%. In the extended region, 100 GeV $< m_{4l} <$ 160 GeV, investigated in this section, their integrated contribution is below 2.5% and is peaking, respectively for the $(Z_1, Z_1)$ and $(Z_2, Z_2)$ pairs, in the regions close to the low and high $m_{4l}$ region boundaries. The above missing phase-space contributions can be thus safely neglected in the studies presented in this paper.

In the following, we compare the predictions of PYTHIA and POWHEG for the Higgs searches background in the $4\mu$ channel as a function of the phase-space cut on the kinematical variable which, as discussed in more details in [3], drives the background peak position in the $m_{4l}$ distribution: the minimal allowed transverse momentum of each of the four leptons, $p_{\mathrm{T},l}$. For this comparison, the PYTHIA distributions were corrected for the missing interference effects using the ratios of the POWHEG distributions obtained by including and excluding the interference effects in the event generation.

In Fig. 5, we show the differential cross section as a function of $m_{4l}$ for the sample of the $4\mu$ events for which $m_{Z_2} > 5$ GeV for the following three $p_{\mathrm{T},l}$ cuts: 5, 7, 10 GeV, and compare the results of the two event generators. We observe a satisfactory agreement within the accuracy of the presented studies of 10% for $p_{\mathrm{T},l}$ cut values of 7 GeV and 10 GeV, while for the $p_{\mathrm{T},l}$ cut value of 5 GeV the background in the Higgs signal region is 20% higher for

[5] This small admixture of the leptonic radiation events arises from the Breit–Wigner tail of the $Z$-resonance.

the PYTHIA predictions compared to the POWHEG ones. As it is the case in DDYP [3], the mass distribution peak position varies with the increasing $p_{\mathrm{T},l}$ cut. It is interesting to point out that the background level in the Higgs peak region, calculated with PYTHIA, varies more rapidly as a function of the $p_{\mathrm{T},l}$ cut value compared to POWHEG.

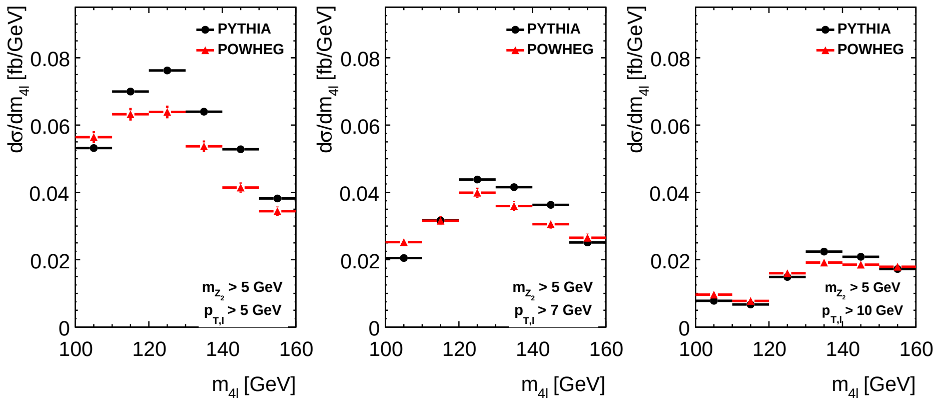


Fig. 5. The $4\mu$ channel PYTHIA and POWHEG differential cross sections as a function of $m_{4l}$ for $m_{Z_2} > 5$ GeV and the minimal $p_{\mathrm{T},l}$ cut values: (left) 5 GeV, (middle) 7 GeV, and (right) 10 GeV. The PYTHIA cross sections are corrected for the missing interference effects using the ratios of the POWHEG distributions obtained by including and excluding the interference effects in the event generation.

We conclude that the effects of including the PS processes producing virtual photons do not appear to change significantly the Higgs searches background level, provided that the $p_{\mathrm{T},l} < 7$ GeV region is avoided. Such a phase-space restriction is justified if the excess events in the $m_{4l} \sim 125$ GeV region are assumed to originate from the Higgs boson decays, producing rarely leptons carrying such a small transverse momentum. However, for the experimental investigation of less theoretically biased scenarios, the $p_{\mathrm{T},l}$ cut should be lowered as much as it is experimentally possible. In such a case, the PS effects will have to be taken into account.

## 5. Testing experimentally importance of PS

For the canonical Higgs searches cuts applied in the ATLAS and CMS analyses [1, 2], the PS effects calculated using the LO PYTHIA generator can be neglected. However, if the phase space for the emission of virtual photons is open not only towards smaller values of $p_{\mathrm{T},l}$ but also towards smaller values of $m_{Z_2}$, our studies indicate that they become important — leading to a stronger increase of the Higgs searches background with decreasing $m_{Z_2}$ than predicted by POWHEG.

This is illustrated in the left and central panels of Fig. 6, showing the differential cross sections as a function of $m_{Z_2}$ for the $4\mu$ event selection satisfying the 100 GeV $< m_{4l} <$ 160 GeV, $p_{\mathrm{T},\mu} >$ 4 GeV and $m_{Z_2} >$ 5 GeV conditions. Indeed, the mass spectrum is steeper in PYTHIA than in POWHEG. The interference and the misassignment effects are significantly smaller in the selected $m_{4l}$ mass region compared to the $Z \to 4l$ region, indicating that the spectra of virtual photon masses are sufficiently distinct for the two generators — to be resolved experimentally.

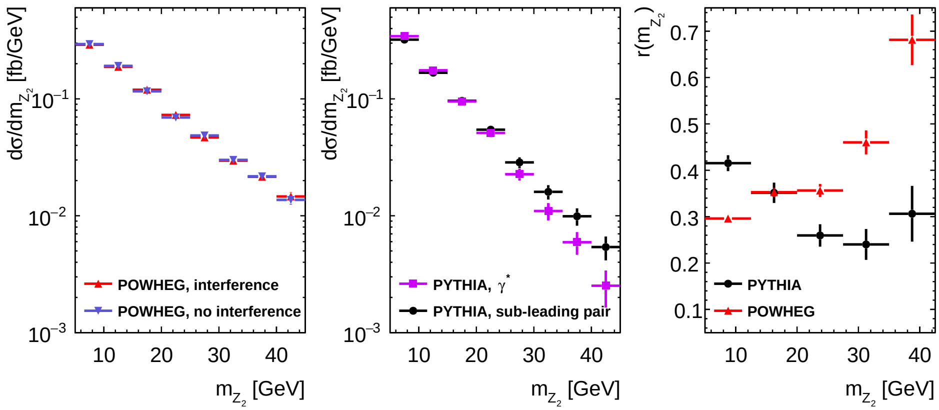


Fig. 6. The comparison of the PYTHIA and POWHEG differential cross sections as a function of $m_{Z_2}$ for the $4\mu$ event sample restricted by the following cuts: 100 GeV $< m_{4l} <$ 160 GeV and $p_{\mathrm{T},\mu} >$ 4 GeV. The interference and the misassignment effects are shown in the left and central panels, respectively. The $r(m_{Z_2})$ ratio, defined in the text, is shown in the right panel for the $4\mu$ event sample restricted by the cuts $p_{\mathrm{T},\mu} >$ 4 GeV and $m_{Z_2} >$ 5 GeV.

The effect of the missing PS contribution for low values of $m_{Z_2}$ may have already been observed in the CMS analysis of the contributions to the $H \to W^+W^-$ background coming from the $W\gamma^*$ production processes [14, 15] — more events were observed than predicted using exclusive ME calculations. This effect was absorbed in [15] within the large value and the large uncertainty of the estimated $K$-factor of $1.5 \pm 0.5$. Such a $K$-factor was necessary to rescale upwards the MAGDRAPH matrix element [16] calculations to match the observed $m_{\mu^+\mu^-}$ spectra in the mass region below 12 GeV for $l^\pm\mu^+\mu^-$ events[6].

[6] Note, that $W\gamma^*$ processes may contribute as background to the Higgs boson signal whenever one of the three leptons in the final state is not selected, no matter what is the mass of the lepton pairs, provided that only one of the two leptons from internal $\gamma^*$ conversion is emitted at sufficiently large transverse momentum.

Concluding the studies presented in this paper, we propose to measure the following precision observable which is particularly sensitive to the parton shower effects

$$r(m_{Z_2}) = \frac{d\sigma/dm_{Z_2}(100\ \mathrm{GeV} < m_{4l} < 160\ \mathrm{GeV})}{d\sigma/dm_{Z_2}(80\ \mathrm{GeV} < m_{4l} < 100\ \mathrm{GeV})}\,. \qquad (1)$$

This ratio is experimentally robust, *i.e.* insensitive to a large fraction of the systematic measurement error sources (they cancel in the ratio). In addition, it is robust with respect to the approximations inherent to the modelling of virtual photon emission in PS. In our view, measurements of such a ratio, preferentially at two LHC collision energies: 8 TeV and 13 TeV, could restrict experimentally the size of the PS effects and assure more robust predictions for the Higgs searches background, with the precision significantly higher than that of the present studies.

In Fig. 6 (right panel), we show the predictions of both event generators for the $r(m_{Z_2})$ ratio, extended down to the values of $m_{Z_2}$ used in the studies of the $Z \to 4l$ decays in [12]. This ratio was calculated for the $4\mu$ events, with each of the 4 muons satisfying the conditions of $p_{\mathrm{T},\mu} > 4$ GeV and $m_{Z_2} > 5$ GeV. The PYTHIA value of $r(m_{Z_2})$ was corrected in this plot for the missing interference effects using the ratios of the POWHEG distributions obtained by including and excluding the interference effects in the event generation.

We see a clear difference between the predictions of the two event generators. They may be resolved experimentally using the collected 7 and 8 TeV data, provided that the analysis is extended to the $m_{Z_2}$ mass region below 12 GeV, where the 30–40% excess of the data with respect to the POWHEG background is predicted[7].

Even if the extension of the $H \to ZZ^*$ acceptance cuts towards lower $m_{Z_2}$ (and lower $p_{\mathrm{T},l}$) would not increase significantly the acceptance for the Higgs decay events, it could replace the belief in the adequacy of the presently available theoretical tools by the confidence in experimentally understanding the Higgs searches background sources.

## 6. Conclusions

The ATLAS and CMS analyses of the irreducible background to the Higgs-boson searches in the four-lepton channels presented in Refs. [1, 2] leave, in our opinion, two open questions:

[7] The difference of the PYTHIA and POWHEG predictions is more pronounced in the $m_{Z_2} > 30$ GeV mass region. However, the number of events in this region collected in the 7 and 8 TeV LHC runs is too small to provide a statistically conclusive test.

1. Can the contribution to the Higgs searches background coming from the quark–gluon scattering processes be neglected?

2. Can the contribution of the processes of high-mass virtual photons emissions by the initial and final state parton showers (PS) be neglected?

In this paper, we have addressed the second question, while the first one will be investigated in detail in a separate publication [8].

Within the precision inherent to the LO-type PYTHIA generator, "calibrated" using the processes of virtual photon emissions by leptons to $\sim 10\%$, the answer to the second question is affirmative. These processes indeed can be neglected at such a precision level for the phase-space cuts applied in the Higgs boson targeted searches [1, 2].

A measurement method tailored for pinning down the PS effects, of particular importance for searches of alternative/complementary mechanisms producing the excess of events in the 125 GeV mass region, has been proposed. This method allows the PS effects to be established experimentally in the PS-sensitive $m_{Z_2} < 12$ GeV mass region, where we predict the 30–40% excess of data with respect to the POWHEG background for the 8 TeV sample of the $4l$ events collected at the LHC. The sensitivity to the PS effects is expected to increase in the subsequent phase of the LHC operation and may become important already for the canonical phase-space cuts.

It would be advantageous if the corresponding experimental studies could be supported on the theoretical side by constructing an MC generator for the four-lepton production processes in which, on top of the POWHEG NLO QCD ME calculations, the interleaved NLO QCD and QED parton showers (including virtual photon emissions) are incorporated.

## REFERENCES

[1] ATLAS Collaboration, *Phys. Lett.* **B716**, 1 (2012); **B726**, 88 (2013); *Phys. Rev.* **D90**, 052004 (2014); CERN-PH-EP-2014-170, to appear in *Phys. Rev.* **D**.

[2] CMS Collaboration, *Phys. Lett.* **B716**, 30 (2012); *Phys. Rev.* **D89**, 92007 (2014).

[3] M.W. Krasny, W. Płaczek, *Acta Phys. Pol. B* **45**, 71 (2014).

[4] M.W. Krasny, W. Płaczek, `arXiv:1501.04569 [hep-ph]`, submitted to *Acta Phys. Pol. B*.

[5] M.W. Krasny, *Acta Phys. Pol. B* **42**, 2133 (2011).

[6] T. Melia, P. Nason, R. Rontsch, G. Zanderighi, *J. High Energy Phys.* **1111**, 78 (2011); P. Nason, *J. High Energy Phys.* **0711**, 040 (2004); S. Frixione, P. Nason, C. Oleari, *J. High Energy Phys.* **0711**, 070 (2007); S. Alioli, P. Nason, C. Oleari, E. Re, *J. High Energy Phys.* **1006**, 43 (2010).

[7] F.A. Berends, W.L. van Neerven, G. Burgers, *Nucl. Phys.* **B297**, 429 (1988).

[8] A. Fedynich, M.W. Krasny, W. Płaczek, in preparation, to be submitted to *Acta Phys. Pol. B*.

[9] T. Sjostrand, S. Mrenna, P.Z. Skands, *Comput. Phys. Commun.* **178**, 852 (2008) [`arXiv:0710.3820 [hep-ph]`].

[10] Hung-Liang Lai *et al.*, *Phys. Rev.* **D82**, 074024 (2010).

[11] A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, *Eur. Phys. J.* **C63**, 189 (2009).

[12] ATLAS Collaboration, *Phys. Rev. Lett.* **112**, 231806 (2014).

[13] ATLAS Collaboration, *Phys. Rev.* **D85**, 72004 (2012).

[14] R.C. Gray *et al.*, `arXiv:1110.1368 [hep-ph]`.

[15] CMS Collaboration, *J. High Energy Phys.* **1401**, 96 (2014).

[16] J. Alwall *et al.*, *J. High Energy Phys.* **6**, 128 (2011).