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THE LHC EXCESS OF FOUR-LEPTON EVENTS INTERPRETED AS HIGGS-BOSON SIGNAL: BACKGROUND FROM DOUBLE DRELL–YAN PROCESS?[*] [**]

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We construct a simple model of the Double Drell–Yan Process (DDYP) for proton–proton collisions and investigate its possible contribution to the background for the Higgs-boson searches at the LHC. We demonstrate that under the assumption of the predominance of short range, $\mathcal{O}(0.1)$ fm, transverse-plane correlations of quark–antiquark pairs within the proton, this contribution becomes important and may even explain the observed excess of the four-lepton events at the LHC — the events interpreted as originating from the Higgs-boson decays: $H \to ZZ^* \to 4l$ and $H \to WW^* \to 2l2\nu$.

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1. Introduction

The recent observation [1, 2] of an excess of events containing a pair of photons, or opposite charge leptons associated with missing transverse energy or two pairs of opposite charge leptons, in the region of invariant

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mass of 125 GeV, has been readily interpreted as a discovery of a new Higgs-like boson. The characteristics of these events have been found to be well described by the present event generators which, on top of the Standard Model (SM) background processes, include the processes of production and decay of the Higgs boson [1, 2].

The road to verify if indeed the signal of the Higgs boson is observed, being pursued now by the CMS and ATLAS experiments, is to measure the coupling strengths, spin and the parity of the particle, believed to be the source of the of excess events. These tests are of indisputable importance. In our view they should, however, be complemented by the experimental exclusion of other mechanisms which may contribute to the observed excess of events, including those which have not been, so far, implemented in the current Monte Carlo generators of the background SM processes due to the lack of an adequate theoretical framework, or the lack of input information, or both.

The mechanisms to be considered must not be in conflict with the present LHC W^+W^- and ZZ production data. The W^+W^- and ZZ cross sections measured by the CMS [3] and ATLAS [4] collaborations are consistently above the theoretical predictions allowing for a possible presence of such mechanisms. It has to be stressed, however, that the statistical significance of the observed excess is weak and the experiments claim the consistency of the measured and predicted values. In the following, we shall assume that any additional mechanism producing the four-lepton events must not increase the overall predicted cross section for the W^+W^- and ZZ on-shell pairs above the measured values.

In this paper, we propose a simple Charged Current (CC) and Neutral Current (NC) Double Drell–Yan Process (DDYP) model. We use this model to investigate a possible, complementary mechanism producing four-lepton events and demonstrate that the DDYP may contribute to, and even explain the Higgs-boson signals in the four-lepton channels presented in [1] and [2]. Finally, we discuss the perspective of discriminating between the above two mechanisms on the experimental ground.

The DDYP has not, so far, been reported as a potential source of the observed excess of events or even as a contribution to the SM background in the Higgs particle searches. This work is, to our best knowledge, a first step in this direction.

2. Double Drell–Yan process

The phenomenological parton-model description of the DDYP process was developed long time ago, see *e.g.* [5]. We follow closely the phenomenological model of [5] and explain below our modifications of this model, and its technical implementation within a Monte Carlo event generator. In the following, we shall ignore the DDYP involving two different protons of each of the colliding particle bunches. We have estimated their contribution to be below the level of 0.1 event for each 1 fb^{-1} of the collected luminosity, *i.e.* negligible.

Our departure point is the canonical, factorized form of the cross section for double Drell–Yan process

$$\sigma^{\mathrm{DDYP}}(p_1,p_2,p_3,p_4) = \frac{\sigma^{\mathrm{SDYP}}(p_1,p_2)\,\sigma^{\mathrm{SDYP}}(p_3,p_4)}{S_{qq}}\,, \tag{1}$$

where p_i are the four-momenta of outgoing leptons (for each allowed e, μ, ν_e and ν_μ combinations), σ^{SDYP} is the Single Drell–Yan Process (SDYP) cross section and S_{qq} can be interpreted as an effective transverse-plane correlation area over which the majority of double-quark annihilations take place. This quantity is denoted frequently in the literature as σ_{eff} or $S_{qq} = \pi R^2$, where R is the equivalent radius of the circle having the surface equal to S_{qq} [5].

This factorized form assumes that the product of double-parton distribution functions: $D_q(x_1,x_2,m_1^2,m_2^2) \times D_q(x_3,x_4,m_1^2,m_2^2)$, where x_i are the fractional longitudinal momenta of annihilating partons, $m_1^2 = (p_1+p_3)^2$, and $m_2^2 = (p_2+p_4)^2$, can be written in form of a product of single-parton densities

$$\begin{aligned} &D_q\left(x_1,x_2,m_1^2,m_2^2\right) D_q\left(x_3,x_4,m_1^2,m_2^2\right) \\ &= q\left(x_1,m_1^2\right) q\left(x_3,m_1^2\right) q\left(x_2,m_2^2\right) q\left(x_4,m_2^2\right)\,. \end{aligned} \tag{2}$$

We assume, that the S_{qq} parameter is independent of the four-momenta of outgoing leptons within the region of the large lepton transverse momenta, $p_{\mathrm{T}}^l \geq 5$ GeV.

There is no experimental information constraining the value of the S_{qq} parameter, contrary to the analogous S_{gg} and S_{gq} parameters representing the transverse plane correlation area for processes in which at least one of the involved partons is a gluon. The latter parameters were derived, using the factorized form of the Double-Parton Scattering (DPS) cross section, from the measured four-jet, three-jet and a photon, and two-jet and a W-boson cross sections by the ISR [6], SppS [7], Tevatron [8] and LHC [9] experiments. They are consistent with a simple model assuming a uniform density of uncorrelated gluons over the transverse area of the proton.

As a starting point to our studies, we have made a simple order-of-magnitude estimation and have found that if $S_{qq} \approx S_{gg}, S_{gq}$, the contribution of the DDYP to the four-lepton production processes is sizeably smaller than the Higgs-boson signal and can be, to a good approximation, neglected. For this contribution to become non-negligible the following condition must be satisfied: $S_{qq} \leq 0.1 \times S_{gg}$. Can one reject *a priori* such a possibility?

There is no reason to expect that the transverse plane of both the quark–quark and antiquark–antiquark correlation areas are sizeably different from the gluon–quark and gluon–antiquark ones. This, however, does not need to be the case for the quark–antiquark pairs.

In the region of $x < 0.01$, relevant to this paper, and at the $Q^2 \approx M_W^2, M_Z^2$ scale, protons are composed almost entirely out of gluons. Their density outnumbers the density of sea quarks by a factor greater than 20. Conversions of gluons decelerated in the colour field of the bulk of the target partons, in the early stage (large Ioffe time [10]), of the proton–proton collisions is the main source of the quark–antiquark pairs, in analogy to photon conversions in the effective electromagnetic field of atoms, rather than individual electrons, being the source of the electron–positron pairs. At the LHC beam energies the effective transverse plane size of the produced quark–antiquark colour and charge dipoles may be significantly smaller than the proton size and must be constrained experimentally. This is especially true for those of the vector bosons pairs that have all their decay products detected in the fiducial volume of the LHC detectors. These pairs are produced by the quark–antiquark pairs which have, preferentially, balanced longitudinal momenta. For such a configuration, the conversions of not only the transversely but also longitudinally polarized virtual gluons must be taken into account.

Motivated by the above considerations, we assume in the following that the dominant contribution to the DDYP cross section comes from the process in which a $q\bar{q}$-pair coming from the sea of one of the colliding process annihilates with a $q\bar{q}$-pair coming from the sea of the second one.

Assuming such a dominance, $\sigma^{\mathrm{DDYP}}(p_1, p_2, p_3, p_4)$ can be expressed as follows:

$$\begin{aligned}
&\sigma^{\mathrm{DDYP}}(p_1, p_2, p_3, p_4) \\
&= \frac{\sigma^{q_s\bar{q}_s}(p_1, p_2)\sigma^{\bar{q}_s q_s}(p_3, p_4) + \sigma^{\bar{q}_s q_s}(p_1, p_2)\sigma^{q_s\bar{q}_s}(p_3, p_4)}{S_{q\bar{q}}}\,,
\end{aligned} \tag{3}$$

where $\sigma^{q_s\bar{q}_s}$ ($\sigma^{\bar{q}_s q_s}$) is the cross section involving q_s ($\bar{q}_s$) coming from the first proton and $\bar{q}_s$ (q) coming from the second one. The corresponding transverse plane correlation area $S_{q\bar{q}}$ of the $q\bar{q}$-pairs for the above process will be kept as a free parameter in our analysis, to be determined from comparisons of such a model to experimental data.

3. Model implementation

The numerical implementation of the DDYP model is based on the Monte Carlo event generator WINHAC [11–13]. It describes the single W/Z-boson production with leptonic decays in hadronic collisions (proton–proton,

proton–antiproton, proton–nucleus, nucleus–nucleus), *i.e.* the CC and NC single Drell–Yan processes. The parton-level hard processes are convoluted with appropriate collinear PDFs taken from the LHAPDF library [14]. The current version of WINHAC includes only the LO QCD matrix elements, however for the W-boson processes it features the $\mathcal{O}(\alpha)$ YFS exclusive exponentiation for the electroweak corrections [11, 12]. At this level, it has been cross-checked numerically to a high precision with independent calculations [15, 16]. In order to generate realistic event shapes, WINHAC is interfaced with the PYTHIA 6.4 generator [17] which performs the initial-state QCD (and QED) parton shower, appropriate proton-remnant treatment and necessary hadronization/decays. This interface provides also improved generation of lepton transverse momenta with respect to the original PYTHIA6 program, which results in a good agreement with the NLO QCD predictions, see [18] for more details.

In the studies presented in this paper, we have used the MSTW2008NLO parametrisation [19] of PDFs. Since in our model only the processes involving the sea quarks are considered, the valence-quark PDFs have been set to zero. The total cross sections for the SDYP have been normalized to the ATLAS and CMS measured values. Thus, for the CC SDYP in WINHAC we have used the following values of the normalisation K-factor: 1.2618 for ATLAS and 1.2840 for CMS. In the case of the NC SDYP, we have used the value of 1.26 for both experiments.

In our simple model, the double Drell–Yan processes are generated as two independent single Drell–Yan processes in which the quarks (antiquarks) come from the opposite proton beams, *i.e.* the two quarks (antiquarks) in a DDYP event have the opposite longitudinal-momentum directions. The longitudinal momenta of the quarks are generated using the standard single-parton PDFs, while their transverse momenta are generated by the PYTHIA generator which includes a Gaussian smearing of the primordial k_{T} with $\sigma_{k_{\mathrm{T}}} = 4$ GeV.

4. Higgs-like signal of DDYP

4.1. ZZ channel

In Fig. 1 (a), we show the shape of the four-charged-lepton invariant-mass distribution in our model of the NC DDYP process at the 8 TeV proton–proton collision energy. This plot includes the sum of the contributions coming from the following four charged lepton combinations: $\mu^+\mu^-\mu^+\mu^-$, $\mu^+\mu^-e^+e^-$, $e^+e^-\mu^+\mu^-$ and $e^+e^-e^+e^-$. The electron energies and the muon transverse momenta were smeared using the parametrized experimental resolution functions of the ATLAS detector [20]. The kinematical cuts on the electron and muon transverse momenta, pseudorapidities, invariant masses of the unlike-charge lepton pairs are the same as the ones used in the ATLAS paper [1]. The only cuts we could not implement are those corresponding to the detector-response related quantities, *e.g.* the lepton isolation cuts.

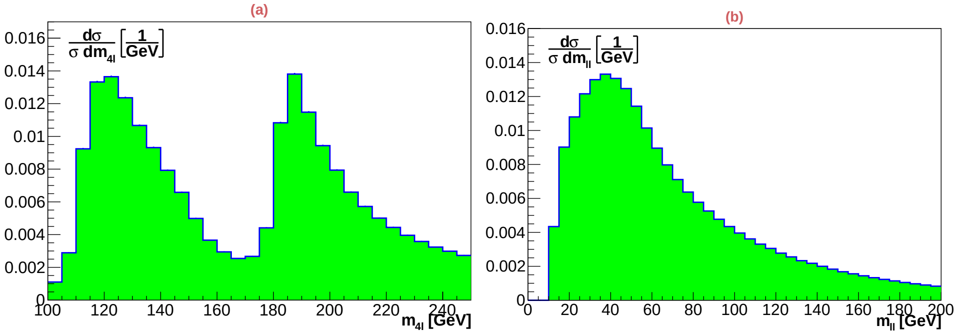


Fig. 1. (a) The $4l$ invariant mass spectrum for the ATLAS event selection criteria [1]; (b) The $e\mu$ invariant mass spectrum for the CMS event selection criteria [2].

Two peaks are clearly visible in this plot: the one for $m_{4l} \approx 2M_Z$ and the second one for $m_{4l} \approx 125$ GeV where the excess of events was reported. While the appearance of the first peak, related to the DDYP production of a pair of Z-bosons, can be expected, the appearance of the second one, in the mass region of the Higgs-like particle candidate, is less trivial. Events in this region are characterized by the invariant mass of the first of the opposite-charge lepton pairs, m_{12}, in the Z-peak region, and the mass of the remaining pair, m_{34}, in the low mass region. The shape of the second peak is driven, for the masses smaller than the peak value, by the experimental cuts: on the minimal allowed transverse momenta of the leptons and on the minimal allowed m_{34} values. For the masses between the peaks, the m_{4l} distribution reflects the $\approx 1/m^2_{l^+l^-}$ shape of the SDYP spectrum.

Note that, within the discussed model, there is no parameter which has been tuned to match the predicted and observed positions of the peak — the peaking behaviour of the DDYP spectrum in the region where the excess of events was observed is a generic feature of the DDYP and the event selection cuts, largely independent of the approximations used in the construction of the model.

The appearance of the second peak, around 125 GeV, of similar magnitude as the first one, puts particular emphasis on the necessity of experimental verification of the importance of the DDYP mechanism. The excess of events in this region cannot, in our view, be (fully) attributed to the Higgs-like particle decays before investigating more closely the DDYP effects. Given the presence of the peaking behaviour in the DDYP spectrum, the Higgs-boson hunting procedure can no longer be confined to a peak search, but must involve a detailed investigation of the excess-events properties. Since both the high-mass and low-mass peaks are of the same amplitude, contrary to the canonical background peaking in the high-mass region only, any procedure of extrapolation of the $4l$ spectra in the monitoring (high-mass) region to the Higgs-like particle signal (low-mass) region may become numerically unstable in the presence of the DDYP mechanism. A small, $\approx 10\%$, shift in the normalisation of the spectra in the monitoring region is reflected by a large, $\approx 50\%$, shift of the predicted background in the Higgs signal region.

4.2. WW channel

In Fig. 1 (b), we show the shape of the two-charged-lepton invariant mass, m_{ll}, distribution in our model of the CC DDYP process for the proton–proton collision energy of 8 TeV. This plot shows the sum of the contributions for the $\mu^- e^+$ and $e^- \mu^+$ combinations, representing the highest signal-to-noise expectations for the Higgs-boson searches. The electron energies and the muon transverse momenta have been smeared using the parametrized experimental resolution functions of the CMS detector [21]. All the kinematical cuts of [2] have been implemented except, as before, the isolation cuts of leptons. The most notable difference with respect to the event selection and event reconstruction procedures presented in [2] is the direct use of generated four-momenta vectors of the neutrino and the anti-neutrino in the calculation of the missing transverse energy, $E_{\mathrm{T}}^{\mathrm{miss}}$, the projected missing transverse energy, $E_{\mathrm{T}}^{\mathrm{miss,proj}}$, and the effective cut on the total transverse hadronic energy, $E_{\mathrm{T}}^{\mathrm{had}}$, which in our paper is used to approximate the selection conditions for the "0-jet" events [2].

As in the case of the four-lepton invariant mass, this plot shows a significant fraction of events in the low m_{ll} region ($m_{ll} \leq 50$ GeV) where the signal of the decay of the 125 GeV Higgs-like particle is expected to show up [2]. Again, any attempt to attribute the excess events observed in this region should, in our view, be preceded by the rejection of the DDYP mechanism as contributing to the background estimation for the Higgs-boson searches.

5. DDYP and Higgs-like particle evidence

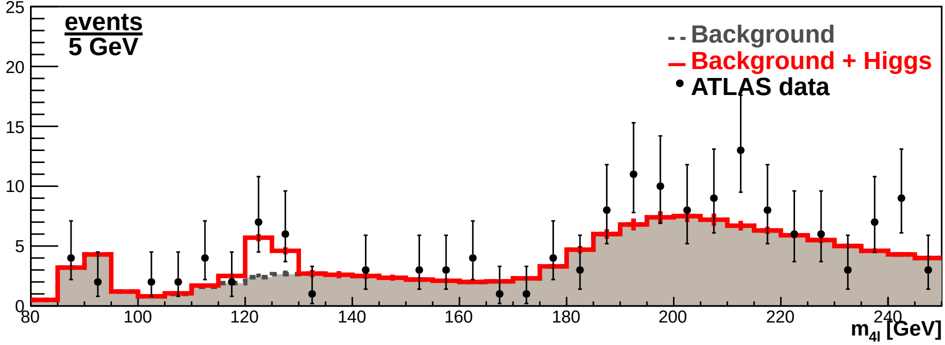
5.1. ZZ channel

Apart from the excess of events in the m_{4l} region of 120–130 GeV, the most striking feature of the m_{4l} distribution presented in [1] is that the predicted background tends to be lower than the data over the full mass region — the ratio of the integrated numbers of the expected-to-observed events in the control region of 160 GeV $< m_{4l} <$ 250 GeV estimated from the plot presented in [1] is 0.8 ± 0.08. Moreover, this ratio hardly changes, to 0.82 ± 0.07, if the integration is made in the full range of the plotted masses[1]: 80 GeV $< m_{4l} <$ 250 GeV.

The overall normalisation of the DDYP contribution in our model cannot be predicted and has to be determined from the data. In the following, we shall investigate what happens if the DDYP is added to the canonical background processes using the normalisation factor which equalizes the total number of predicted and observed events.

In Fig. 2, we compare the m_{4l} plot presented in [1], in which the observed event distribution is compared to sum of the background and the contribution of the Higgs-boson decays, with an analogous plot in which,

(a) ATLAS results



(b) DDYP predictions

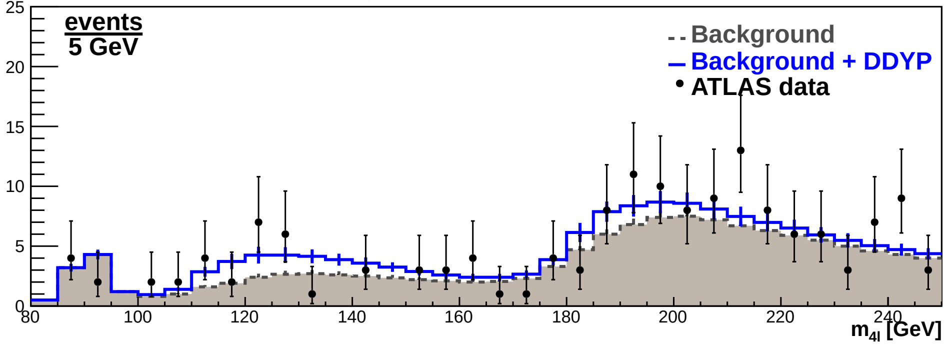


Fig. 2. The $4l$ invariant-mass spectrum: (a) as presented by the ATLAS Collaboration in [1] and (b) with the Higgs-boson signal replaced by the DDYP contribution.

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[1] Unfortunately, the CMS Collaboration does not show the ZZ peak in its paper [2], therefore this trend cannot be verified directly using the CMS data. There is, however, an indication, coming from the CMS measurement of the total ZZ-pair cross section presented in [3], that the measured cross section is ∼ 10% higher than the theoretical predictions.

instead of the Higgs-boson contribution we have added the contribution of DDYP. The DDYP contribution was normalized such that the integrals corresponding to the data and to the background contributions presented in [1] plus the DDYP are equal. This plot has been obtained by merging two results: for the 7 TeV and 8 TeV proton–proton collision energies with the respective weights, representing the corresponding fractions of the collected total luminosity. The quality of the overall fit of the data for the "background+Higgs" hypothesis, $\chi^2/\text{d.o.f.} = 1.15$, is slightly worse than the one for the "background+DDYP" hypothesis, $\chi^2/\text{d.o.f.} = 1.04$, but both are equally acceptable; the corresponding p_0-values are respectively: $p_0 = 0.25$ and $p_0 = 0.41$.

5.2. WW channel

Both the ATLAS [1] and CMS experiments [2] observe an overall excess of events in the $e\mu\nu\nu$–"0-jet" final state with respect to the predicted background in the analysed kinematical region. In order to circumvent this mismatch, both experiments scaled up the background contribution in the kinematical region in which the decays of the 125 GeV Higgs boson do not contribute. They extrapolated subsequently the scaled-up spectra to the kinematical region where the Higgs decay contribution may show up, for more details, see [1] and [2].

Since we do not have access to the unscaled distributions, we cannot construct, as in the case of the ZZ channel, appropriate plots which would include the sum of the background determined in [1, 2] and the DDYP contribution. We can, however, use the measurement of the total W^+W^- cross section at 8 TeV, recently published by the CMS Collaboration [3], in order to evaluate a possible contribution of the DDYP mechanism to the spectrum of the two-charged-lepton invariant mass, m_{ll}, under the assumption that the inclusion of this process restores the agreement between the measured, $\sigma_{\text{exp}}(W^+W^-) = 69.9 \pm 2.8\,(\text{stat.}) \pm 5.6\,(\text{syst.}) \pm 3.1\,(\text{luminosity})\,\text{pb}$, and predicted, $\sigma_{\text{th}}(W^+W^-) = 57.3^{+2.4}_{-1.6}\,\text{pb}$, values of the cross section. It is intriguing to note that the ratio of the predicted to the observed cross sections, equal to 0.82 ± 0.08, is the same as the corresponding ratio for the $4l$ channel.

The main difference of such a procedure, with respect to the one used in the previous section, is that one becomes sensitive to all the detector-dependent contributions to the event-selection efficiency other than those related to kinematical cuts, for example the lepton trigger and isolation efficiencies[2]. Our predicted contribution of the DDYP, discussed below, represents thus its upper limit.

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[2] In the case of the $4l$ channel, we rely only on the independence of the above efficiencies on the m_{4l} value.

As shown in [2], the decays of the 125 GeV Higgs particle contributes to the m_{ll} spectrum mainly in the region $m_{ll} < 50$ GeV. Using this result, we have estimated that in this region and for the integrated luminosity of 5.1 fb^{-1} about 27 ± 5.4 events are predicted to originate from the Higgs-boson decays. Our estimated upper limit of the corresponding hypothetical contribution of the DDYP in this kinematical region, determined using our model normalized to the difference of the measured and the predicted WW cross sections, is 32 ± 17 events.

Our conclusion from the above exercise is the same as before for the ZZ channel. If we assume that the 2σ excess of the measured over predicted cross sections is not a statistical fluctuation but a real effect (this conjecture is supported by the observation of a similar excess of events in both the ZZ and WW channels), the observed excess of events in the $m_{ll} < 50$ GeV region can be attributed to the DDYP source. Thus, again, on a purely experimental ground, we are unable to discriminate between the two hypotheses: (1) that the excess of events in the WW channel is due to the Higgs-boson signal and (2) that the excess of events in the WW channel is due to the DDYP contribution.

6. Quark–antiquark transverse-plane correlation area

The quark–antiquark transverse plane correlation area, $S_{q\bar{q}}$, is the only parameter of the model discussed in this paper. Its value determines the overall normalisation of the DDYP contribution.

For the WW final state, $S_{q\bar{q}}$ is determined directly from absolute normalisation of the DDYP cross section to the difference between the measured and the predicted W^+W^- cross sections by the CMS Collaboration [3]. The resulting value is $S_{q\bar{q}}^{W^+W^-} = 0.075 \pm 0.04\,\mathrm{mb}$.

For the ZZ final state, we are bound to make an assumption concerning the lepton-isolation efficiency, $\epsilon_{\mathrm{isol}}^{1}$, which is driven by the detector-dependent cuts and, therefore, cannot be implemented fully in our analysis. We have assumed a rather conservative allowed range for the "per-charged-lepton" efficiency: $0.8 < \epsilon_{\mathrm{isol}}^{1} < 1.0$ to constrain the $S_{q\bar{q}}$ parameter by normalizing the calculated DDYP predictions to the difference of the predicted and the observed numbers of events in the m_{4l} plot. The resulting value is $S_{q\bar{q}}^{ZZ} = 0.14 \pm 0.07\,\mathrm{mb}$.

It is intriguing to note that the above values are compatible with the transverse size of the W and Z boson production zone, Δr_{T}, determined from the Heisenberg uncertainty principle: $\Delta k_{\mathrm{T}} \Delta r_{\mathrm{T}} \simeq 1$, assuming $\Delta k_{\mathrm{T}} =$ 4 GeV — the value used in the non-perturbative smearing of the primordial transverse momentum of annihilating quarks in PYTHIA.

It is also very important to stress that the average transverse plane correlation area of the quark–antiquark pairs $S_{q\bar{q}}$ must, within our model, be a factor $\mathcal{O}(10)$ smaller than the corresponding ones for the gluon–gluon and gluon–quark pairs, for the contribution of the DDYP to the four-lepton spectra to be non-negligible, and a factor $\mathcal{O}(100)$ smaller for the full attribution of the observed excess of events to the DDYP source[3]. The latter hypothesis, corresponding to the predominance of the short range, $\mathcal{O}(0.1)$ fm transverse-plane correlations of the quark–antiquarks pairs within the proton, even if at the first sight unrealistic, should, in our view, be investigated experimentally before it can be rejected.

7. Caveats

The phenomenological framework which has been used in the presented above analysis is obviously crude. The DDYP model is formulated using the probabilistic language rather than the one based on quantum-mechanical amplitudes. It neglects the colour, spin, flavour as well as longitudinal and transverse momenta correlations of the initial partons. They certainly play an important role, in particular for the small $S_{q\bar{q}}$ region. It assumes that all the proton–quarks and antiquark pairs are coming from the $S_{q\bar{q}}$ transverse-plane region. Finally, it neglects both the interference terms of the amplitudes of the DDYP processes with other sources of the vector–boson pairs, and, in the case of ZZ^* production, the interference of diagrams with exchanged lines of the same flavour and charge leptons.

A significant progress has been made recently in formulating the sound theoretical framework for a general description of the Double-Parton Scattering (DPS) processes in the proton–proton collisions. For a review of the recent progress, see [22, 23] and the references quoted therein. One of the most important aspects of the present understanding of DPS, which is of critical relevance for the DDYP in the small $S_{q\bar{q}}$ regime considered in this paper, and which was discussed in details in [24], is a correct theoretical handling of the DPS collinear singularity in the quark-loop integrals. The correct handling should take into account the differences in the impact-parameter correlations of partons emerging from perturbative and non-perturbative processes and should avoid the double counting of the single gluon–gluon scattering and the double-parton scattering contributions. While the former has already been taken into account in the evaluation of the background for the Higgs-boson signal in [1, 2] by using the gg2ZZ [25] and gg2WW [26]

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[3] The above numbers may be modified in the case of presence of new initial or final-state interactions, specific to the colour-singlet, charge-neutral and spin-zero four-quark system, or to the W^+W^- and ZZ boson pairs, produced at distances comparable to $1/\Gamma_W, 1/\Gamma_Z$.

event generators, the latter has not been, so far, reported as a potential additional source of the four-lepton events at the LHC. The importance of this point is amplified by the fact that, in the selection of the Higgs-boson candidates decaying into pairs of W and Z bosons [1, 2], neither a cut on the minimal absolute and relative transverse momenta of the corresponding lepton pairs, nor a cut on the minimal transverse momentum of the recoil hadronic system has been applied. The absence of such cuts exposes any future calculation of the DDYP background for the Higgs-boson searches to the collinear and soft enhanced effects, discussed *e.g.* in [22].

The theoretical progress in the DPS framework has not been, so far, reflected in development of phenomenological tools allowing to study the DPS processes, in particular the DDYP, with realistic experimental cuts. A corresponding DDYP event generator, using generalized two-parton distribution functions, taking into account the longitudinal-momentum as well as the transverse-impact-parameter correlations between the quark and the antiquark, and including the colour, flavour and spin correlations simply does not exist. It is better, in our view, to construct a crude model and investigate its consequences, rather than to ignore *a priori* the DDYP mechanism altogether in the analysis of the background contribution to the Higgs-boson searches, for the reason that no precise technical tool exists. Obviously, the model presented in this paper cannot be more than an initial tool for the investigation of the potential importance of the DDYP contribution to the Higgs-boson searches. A tool which allows us to define the critical experimental tests to discriminate between the DDYP and Higgs-boson mechanisms. Being fully aware of all the theoretical caveats of the DDYP model presented in this paper, we shall discuss in the next section how the hypothetical contribution of the DDYP to the background of the Higgs-boson searches can be rejected experimentally in a way which is the least dependent on our model approximations.

8. Falsification of DDYP contribution

As discussed in Section 5, on the basis of the data presented in [1] and [2] one cannot discriminate, on purely experimental ground, between the following two hypotheses:

1. The observed excess of events in the WW^* and ZZ^* channels is entirely due to the production of the Higgs-like particle.
2. The excess events is produced partially, or entirely by the DDYP mechanism.

In order to define the critical experimental tests, which may be used in the analysis of the full statistics of events recorded till now at the LHC, we should first identify which event characteristics are similar in the two processes and which are distinct. Let us first identify where the DDYP contribution will be hardly distinguishable from the Higgs-boson signal.

- The peaking behaviour in the four-lepton mass spectrum in the region of the observed excess of events: in the case of the Higgs-boson signal the peak position reflects the Higgs-boson mass, whereas in the case of the DDYP it is driven both by the experimental cuts and by the remaining small sensitivity to the assumption concerning the quark and antiquark distributions.
- The DDYP, initiated by the annihilation of the two quark–antiquark dipoles, produces a pair of electroweak bosons of the preferentially opposite polarisations, mimicking perfectly the decays of a scalar particle.
- If the gluons are the main origin of the small size quark–antiquark dipoles, the relative CM-energy dependence of the DDYP effect and the Higgs-boson signal are similar, thus there is hardly any gain from the method proposed in [27] to distinguish between these two mechanisms on the basis of the measurement of the cross-section ratios at two different CM-energies of the proton–proton collisions.
- The DDYP process mimics the custodial symmetry of the Higgs-boson coupling pattern to the Z and W bosons, in the sense that it generates the same relative excess of events with respect to the corresponding canonical leading-twist SM background processes for the WW and ZZ channels.

There are, however, several characteristics of the DDYP events which, independently of the approximations of the present DDYP model, allow reject the hypothesis that the DDYP is the source of the observed excess of events.

- The position of the peak for the Higgs-boson signal is invariant with respect to kinematical cuts, while the position of the DDYP peak is cut-dependent.
- The excess of events in the region of the 125 GeV peak must be accompanied for the NC DDYP by the excess of events in the $m_{4l} > 2M_Z$ region (for the WW channel by the excess in the $m_{ll} > 80$ GeV region). Obviously, the decays of the 125 GeV Higgs boson does not contribute to the high-mass regions.

- The width of the 125 GeV peak, in the case of the Higgs-boson signal, is driven only by the detector experimental resolution which, for the $4l$ channel, is of the order of 2 GeV for both experiments. In the DDYP case, the peak is significantly broader — its width reflects both by the experimental cuts and the $m_{l^+l^-}$ dependence of the SDYP cross section.

The above differences are generic, *i.e.* largely independent of our DDYP model approximations and may be used in the experimental tests allowing to discriminate between the Higgs-boson and DDYP sources of the excess of events.

As long as the LHC collaborations will not publish the distributions unfolded for the experimental effects, these tests can be done, in the fully quantitative way, only by the LHC collaborations.

In the following we present, as an illustration, a concrete example of such tests: the study of the DDYP peak position as a function of the experimental cut on the minimal allowed transverse momentum of each of the leptons. The studies presented below cannot be directly compared to the ATLAS and CMS data. They are made for an ideal detector for which the selection efficiencies of isolated leptons are independent of their traverse momenta and of the lepton family.

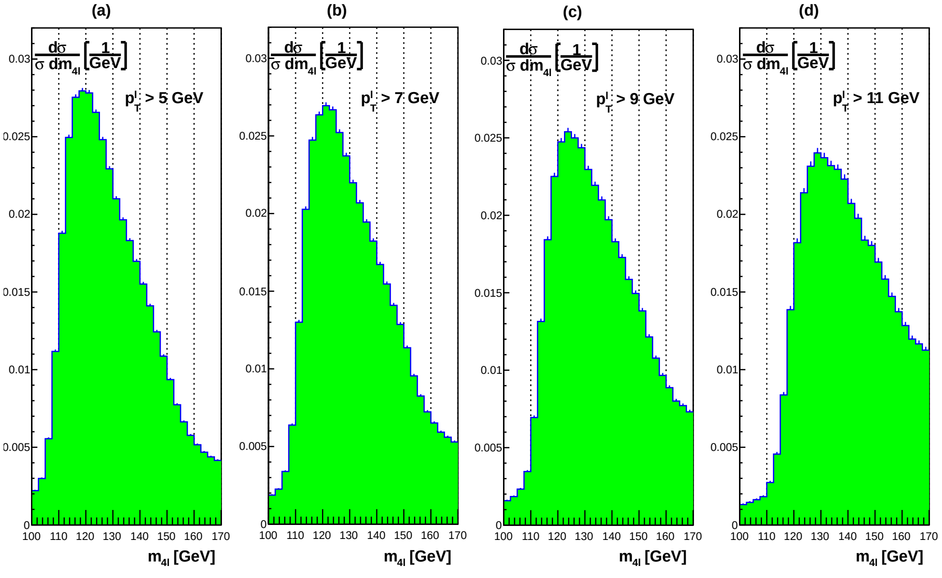

Fig. 3. The $4l$ invariant-mass distributions for the following cuts on the minimal transverse momentum of each of the four charged leptons: (a) 5 GeV, (b) 7 GeV, (c) 9 GeV and (d) 11 GeV.

In Fig. 3, we show the evolution of the DDYP peak position as a function of the lepton minimal p_{T}^{l} cut for the cut values of 5, 7, 9 and 11 GeV. The peak positions were determined using the third-degree polynomial fit. They are, respectively: 119.1 ± 1.3, 121.1 ± 1.3, 124.2 ± 1.3, and 129.9 ± 1.3 GeV. A significant variation of the peak position as a function of the p_{T}^{l} is observed. Its measurement, using the unfolded m_{4l} distributions, could put a stringent constraint on the importance of the DDYP contribution to the Higgs searches background.

The present p_{T}^{l} cut values which are implemented in the ATLAS and CMS Higgs searches [1, 2] are 7 (6) GeV for electrons (muons) in the ATLAS case, and 7 (5) GeV for electrons (muons) in the CMS case. If the DDYP is the dominant source of the events in the m_{4l} peak region then any observed differences in the peak positions for the ATLAS and CMS data, and for the 4μ and $4e$ channels could be attributed to the respective differences in the p_{T}^{l} cuts[4]. In our DDYP model, the peak position for the 4μ events is predicted to be shifted to a smaller m_{4l} value than that for the $4e$ events. Under the assumption of the same p_{T}^{l} dependence of the electron and the muon selection and isolation efficiencies, the predicted shift is 2 GeV for the present CMS cuts and by a factor of 2 smaller for the ATLAS ones.

9. Conclusions and outlook

In the presented paper, we have argued that on the basis of the published data the DDYP and Higgs-boson production mechanisms cannot be discriminated — they provide equally good description of the observed distributions. In order to assure, beyond any doubt, that the observed excess of events is entirely due to the Higgs-like boson decays, rather than the hypothetical DDYP contribution, the latter should be rejected on purely experimental grounds.

If the DDYP contribution is found to be non-negligible, its detailed study could allow, for the first time, to investigate experimentally the quark–antiquark correlations within the proton, and to make an important progress in our basic understanding of the relationship between the QCD and the proton structure. Strangely enough, 40 years after the QCD was proven to be the theory of the strong interactions, the question: “What is the underlying

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[4] Note that the $m_{\min}$ cut [1, 2] is set in the above studies to 12 GeV — the value implemented now by both the ATLAS and CMS collaborations. We have checked that the peak positions, for the studied range of the p_{T}^{l} cuts, are stable with respect to adding the ATLAS specific linear rise of the $m_{\min}$ cut in the m_{4l} range up to 190 GeV. We have also checked that the effective cut on the minimal allowed p_{T}^{l} for the third lepton (if arranged in the order of decreasing p_{T}^{l}) of 10 GeV, specific for the ATLAS selection criteria, affects only a negligible fraction of the selected CMS events.

mechanism which correlates the quark and antiquark longitudinal momenta and their transverse impact-plane positions within the proton over the distances equal or smaller than the size of the proton?" cannot be answered by the QCD and must be resolved experimentally.

The DDYP provides not only the experimentally cleanest, but also the most comprehensible environment for such studies. The relative strength of the CC DDYP in the $W^+W^+ + W^-W^-$ *versus* $W^+W^- + W^-W^+$ processes could resolve the transverse-plane correlations of the quark–quark pairs with respect to the quark–antiquark ones. Moreover, the relative strength of the DDYP effects in the proton–proton and proton–nucleus collisions could provide a crucial experimental insight into the relative importance of the short-distance (smaller that the nucleon size) and long-distance (comparable to the nucleon size) transverse-plane correlations of the quarks and antiquarks within nucleons.

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