Estimates of Z' couplings within data on the A_{FB} for Drell-Yan process at the LHC at $\sqrt{s} = 7$ and 8 TeV

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A model-independent search for the Abelian Z' gauge boson in the Drell-Yan process at the LHC at $\sqrt{s} = 7$ and 8 TeV is fulfilled. Estimations of the Z' axial-vector coupling a_f^2 to the standard model fermions, the couplings of the axial vector to lepton vector currents $a_f v_l$, and the couplings of the axial vector to quark vector currents $a_f v_q$ are derived within data on the forward-backward asymmetry presented by the CMS Collaboration. The analysis takes into consideration the behavior of the differential cross section, which exhibits itself if the derived already special relations between the couplings proper to the renormalizable theories are accounted for. In particular, they hold in all the models of Abelian Z' usually considered in the model-dependent analysis of the LHC data. The coupling values are estimated at ~92% confidence level by means of the maximum likelihood function. They weakly depend on the Z' mass in the investigated interval 1.2 TeV $< m_{Z'} <$ 5 TeV. Taking into account the dependence of $Z - Z'$ mixing angle θ_0 on $m_{Z'}$ and the LEP constraints $|\theta_0| \sim 10^{-3}$–10^{-4}, the optimistic limits on $m_{Z'}$ are established as $3 < m_{Z'} <$ 7–8 TeV. Comparison with the results of other authors is given.

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I. INTRODUCTION

Since the discovery of the Higgs boson at the LHC, the standard model (SM) has been considered complete. From a "practical" computational point of view this means that the neutral scalar particle of the mass 125 GeV has to be taken into consideration for all the processes investigated. If we also believe that the spontaneous symmetry breaking mechanism is operating to supply particle masses, the Higgs field has to be considered a fundamental state, which must enter any renormalizable theory. This also concerns new models extending the SM at high energies and containing various scalar particles.

Searching for new physics is the main goal of experiments at the LHC. One of the expected heavy particles is an Abelian Z' gauge boson predicted by numerous extended models (see review papers [1–2]). It is introduced as the field related with an additional $\tilde{U}(1)$ group to the SM gauge group. Lower bounds for its mass have been obtained at the LEP ([3–5]), Tevatron [6], and first run LHC experiments [2] in either model-dependent or model-independent approaches. The present-day model-dependent published lower bound on the mass is $m_{Z'} > 2.5$ TeV from the CMS results and $m_{Z'} > 2.9$ TeV from the ATLAS ones. At present about hundred Z' models are discussed in the literature. In model-dependent searches established, only the most popular ones such as LR, ALR, χ, ψ, η, B—L, and SSM, have been investigated and the particle mass is estimated. These models are also used as benchmarks in introducing the efficient observables for future experiments at the ILC [7–8]. In this approach, the couplings to the SM particles were fixed as in the specific considered models and therefore not estimated. As it also occurred, the identification reach for different models is about the estimated $m_{Z'}$ lower masses. So it is problematic to distinguish the basic Z' model at the LHC. In such a situation, model-independent approaches are also very promising. They give a possibility for estimating not only the particle mass but also some Z' couplings to the SM fermions. Hence, definite classes of the extended models could be restricted.

In studies of perspective variables for identification of the Z' models [8], in particular, it was concluded that, as a complementary way, a model-independent approach is very desirable. Estimations of couplings can be further used in specifying the basic Z' model. Usually, the couplings are considered independent arbitrary numbers. However, this is not the case and they are correlated parameters, if some natural requirements, which this model has to satisfy, are assumed. In most cases we believe that the basic model is a renormalizable one. Hence, correlations follow and the amount of free parameters reduces. Moreover, the correlations between couplings influence kinematics of the processes that gives a possibility for introducing the specific observables that uniquely pick out the virtual state of interest, the Z' boson in our case. The noted additional requirement assumes searching for new particles within the class of renormalizable models. In other respects the models are not specified. Below, we call the analysis a model-independent approach when either the mass or the couplings must be fitted. Such a type of approach is in between the usual model-dependent method, when all the

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couplings are fixed and only the mass $m_{Z'}$ is a free parameter, and model-independent searches assuming complete independence of couplings describing new physics. A recent review on searching for the Abelian Z' boson in the model-independent approach is [9].

In what follows, we search for the Abelian Z' boson belonging to a renormalizable model. We also assume that there is only one additional heavy particle relevant at considered energies. There are numerous models of this type. In particular, most of the E_6 motivated models and those mentioned above enter this class. Those used in the present analysis relations (5) are proper to this class. In particular, they hold in the models noted above. These relations have been derived already in two ways [10–11]. For the convenience of readers, we adduce more details about them in Appendix B. In what follows, we say Z' boson for the Abelian one only. We also assume that the SM is the subgroup of the extended group and therefore no interactions of the type $ZZ'W^+W^-$ appear in the tree-level Lagrangian.

In the present paper, we search for the Z' at the LHC on the basis of the CMS data on the forward-backward asymmetry, A_{FB}, for the Drell-Yan annihilation process measured at energy $\sqrt{s} = 7$ [12] and 8 TeV [13]. As we show below, this observable is finely sensitive to the Z' signals due to kinematics properties of the differential cross sections of the process. The advantage of the Drell-Yan process is that it is a "pure" one and we do not need to take the hadronization effects into consideration. We suppose that in this process the Z' manifests itself as the intermediate state like the Z boson and the photon. But it is a heavy particle and all the loops of it are decoupled at investigated energies. As a result, the Z' exhibits itself as the special kind of external field. It modifies the observables as compared to the SM predictions. In paper [12] presented by the CMS collaboration it is noted that all the measured A_{FB} values are in agreement with the SM expectations at 1–2σ confidence level (C.L.). So there is no indication of new physics. However, in those data there is a significant number of the points located closely to the C.L. area boundary. So it is of interest to verify whether the data on A_{FB} could result in signals (hints, in fact) for a new heavy particle—the Abelian Z' gauge boson.

The A_{FB} of the Drell-Yan lepton-antilepton pair is chosen as the observable for the experimental data processing. Reasons for this are discussed in the next section. This quantity turns out to be very sensitive to small changes of used parameters. Also, its theoretical uncertainty, which originates from the parton distribution function (PDF) uncertainty, is much smaller than the one of the total cross sections. Thus, the A_{FB} yields quite precise results for measured quantities. Also, in a recent paper [14] the complementarity of the A_{FB} to the total cross section was motivated in searching for the Z' as a resonance state. Our model-independent analysis supports this idea for lower beam energies. In fact, within a huge amount of data accumulated at the LHC at different energies one is able to estimate various important parameters that could be used in further studies.

As we show, the CMS data on the A_{FB} admit the Z' existence. By using the maximum likelihood function method we estimate the Z' couplings to the SM fermions for the Z' mass in the interval 1.2 TeV $< m_{Z'} <$ 5 TeV and obtain that these couplings are to be nonzero with the 92% C.L. accuracy. Taking into account the estimated value of a_f^2 and the experimental upper bound on mixing angle $|\theta_0| \sim 10^{-3}$–10^{-4} [15] the estimates of the mass $3 < m_{Z'} <$ 7–8 TeV are derived.

The paper is organized as follows. In the next section we present the cross sections of the process investigated and its angular distributions at various values of the effective mass for lepton pairs. The observed behavior of different factor functions entering the cross section gives reasons for introducing the A_{FB} as a convenient observable. In Sec. III the estimations of the couplings are carried out. Section IV is devoted to discussion and comparison with the results of other authors. In Appendix A, we present the behavior of the F_k factors entering Eq. (13). Appendix B contains necessary information about Eqs. (4) and (5). Appendix C includes detailed information about the PDF uncertainties.

II. CROSS SECTION WITH THE Z'

In this section, we calculate the cross section of the Drell-Yan process in the model-independent approach and obtain its dependence on the Z' couplings.

We start with the differential cross section in the parton model written in the Collins-Soper frame [16],

$$\frac{d^3\sigma}{dMdYdz} = \sum_q M\left[\tilde{f}_q\left(\frac{M}{\sqrt{s}}e^{Y}\right)\tilde{f}_{\bar{q}}\left(\frac{M}{\sqrt{s}}e^{-Y}\right)\frac{d\hat{\sigma}_q(z)}{dz} + \tilde{f}_q\left(\frac{M}{\sqrt{s}}e^{-Y}\right)\tilde{f}_{\bar{q}}\left(\frac{M}{\sqrt{s}}e^{Y}\right)\frac{d\hat{\sigma}_q(-z)}{dz}\right]. \quad (1)$$

Here, $\hat{\sigma}$ is the parton-level cross section, $\hat{\sigma}_q \equiv \sigma_{q\bar{q}\to l^+l^-}$, and l^+l^- are final lepton states. Everywhere below we denote the parton-level quantities with the hatted letters and the appropriated hadron-level quantities, which are already integrated with PDFs, with the nonhatted ones. M is the dilepton invariant mass, Y is an intermediate state rapidity, and $z = \cos\theta_{CS}$, where θ_{CS} is a dilepton scattering angle. We take into account the known relations between the quark x_1 and antiquark x_2 momentum fractions: $x_{1,2} = (M/\sqrt{s})e^{\pm Y}$. The functions $f_q(x)$ are the PDF distributions, and the functions $\tilde{f}_q(x) = xf_q(x)$ are preimplemented in the majority of PDF computer packages. In (1) we sum over the quarks only, not over both the quarks and antiquarks.

To proceed we have to calculate the parton-level cross section $\hat{\sigma}_{q\bar{q}\to l^+l^-}$ taking into account the Z' contributions. The effective low energy Lagrangian describing the interaction of the heavy Z' with the SM particles was introduced in [17–18]. Its part related to our problem and describing interactions between the fermions and the Z and Z' mass eigenstates reads (see, for example, [9])

$$\mathcal{L}_{Z\bar{f}f} = \frac{1}{2} Z_\mu \bar{f}\gamma^\mu [(v_{fZ}^{\rm SM} + \gamma^5 a_{fZ}^{\rm SM}) \cos\theta_0 + (v_f + \gamma^5 a_f) \sin\theta_0] f, \quad (2)$$

$$\mathcal{L}_{Z'\bar{f}f} = \frac{1}{2} Z'_\mu \bar{f}\gamma^\mu [(v_f + \gamma^5 a_f) \cos\theta_0 - (v_{fZ}^{\rm SM} + \gamma^5 a_{fZ}^{\rm SM}) \sin\theta_0] f, \quad (3)$$

where f is an arbitrary SM fermion state; $v_{fZ}^{\rm SM}$ and $a_{fZ}^{\rm SM}$ are the SM axial-vector and vector couplings of the Z boson, a_f and v_f are the ones for the Z', and θ_0 is the Z–Z' mixing angle. Within the considered formulation, this angle is determined by the coupling $\tilde{Y}_\phi$ of fermions to the scalar field as follows (see [9] and Appendix B for details),

$$\theta_0 = \frac{\tilde{g} \sin\theta_W \cos\theta_W}{\sqrt{4\pi\alpha_{\rm em}}} \frac{m_Z^2}{m_{Z'}^2} \tilde{Y}_\phi + O\left(\frac{m_Z^4}{m_{Z'}^4}\right), \quad (4)$$

where θ_W is the SM Weinberg angle, $\tilde{g}$ is the $\tilde{U}(1)$ gauge coupling constant, and $\alpha_{\rm em}$ is the electromagnetic fine structure constant. Although the mixing angle is a small quantity of order $(m_Z^2/m_{Z'}^2)$, it contributes to the Z-boson exchange amplitude and cannot be neglected.

As was shown in [9–11], if the extended model is renormalizable and contains the SM as a subgroup, the relations between the couplings hold,

$$v_f - a_f = v_{f^*} - a_{f^*}, \qquad a_f = T_{3f} \tilde{g} \tilde{Y}_\phi. \quad (5)$$

Here f and f^* are the partners of the $SU(2)_L$ fermion doublet ($l^* = \nu_l$, $\nu^* = l$, $q_u^* = q_d$ and $q_d^* = q_u$); T_{3f} is the third component of the weak isospin. These relations are proper for the models of Abelian Z'. They are just as in the SM for proper values of the hypercharges Y_f^R, Y_f^L, Y_ϕ of the left-handed and right-handed fermions and scalars. The correlations can be derived from the necessary requirement of renormalizability that there are no new divergent structures appearing in one-loop order. The divergencies could appear at the structures presented in the initial tree-level Lagrangian only. If these conditions do not hold, the theory is not renormalizable. But if they fulfil one-loop order, there is no guarantee that this will be the case in higher orders or when accounting for anomalies. The latter two questions are more delicate. They require detailed information about the particle content of the model. Thus, the correlations (5) are the necessary conditions for renormalizability. Another way of deriving (5) is presented in Appendix B.

The couplings of the Z' to the axial-vector fermion current have a universal absolute value proportional to the Z' coupling to the scalar doublet. Then the Z–Z' mixing angle (4) can be determined by the axial-vector coupling. As a result, the number of independent parameters is significantly reduced. This universality follows due to exchange of the scalar particles. In particular, the relations (5) hold in the two-Higgs-doublet SM (see Appendix B). Because of the universality, we omit the subscript f and write a for the axial-vector coupling. It is convenient for what follows to introduce the normalized couplings,

$$\bar{a} = \frac{1}{\sqrt{4\pi}} \frac{m_Z}{m_{Z'}} a, \qquad \bar{v}_f = \frac{1}{\sqrt{4\pi}} \frac{m_Z}{m_{Z'}} v_f. \quad (6)$$

As it follows from (2) and (3), the Drell-Yan process cross section has the contribution from the SM, the Z–Z' interference, and the Z' part. The last contribution can be neglected at energies not close to a Z' resonance peak. Hence, taking into account (5), the parton-level cross section can be written as

$$\frac{d\hat{\sigma}_q}{dz} = \left(\frac{d\hat{\sigma}_q}{dz}\right)_{\rm SM} + \bar{a}^2 \hat{F}_{q1} + \bar{a}\bar{v}_l \hat{F}_{q2} + \bar{a}\bar{v}_u \hat{F}_{q3} + \bar{v}_l \bar{v}_u \hat{F}_{q4}, \quad (7)$$

where $\hat{F}_{qk} = \hat{F}_{qk}(M, z)$ are known from calculation kinematics factors, q in the subscript is u or d (for up and down quarks, respectively), subscript l denotes the Z' to lepton coupling, and subscript u denotes the Z' to up-quark coupling. Thus, there are four unknown parameters that should be estimated from experiments. However, due to obvious relation $a^2 \bar{v}_l \bar{v}_u = \bar{a}\bar{v}_l \bar{a}\bar{v}_u$ the parameter $\bar{v}_l \bar{v}_u$ can be expressed through three others. So, in general, a three-parameter fit is needed. Let us check whether it is possible to find an integral observable containing fewer unknown parameters.

To do that we consider the behavior of the $\hat{F}_{qk}$ functions. In our analysis, these functions were calculated in an improved Born approximation in one-loop order. In the $Z - Z'$ interference part, the loops with the SM particles coming from the Z' exchange part were computed analytically whereas the SM contributions have been calculated by using the PYTHIA package.

We investigate the behavior of the hadron-level factors

$$F_k(M, Y, z) = \sum_q M \left[\tilde{f}_q\left(\frac{M}{\sqrt{s}} e^Y\right) \tilde{f}_{\bar{q}}\left(\frac{M}{\sqrt{s}} e^{-Y}\right) \hat{F}_k(M, z) + \tilde{f}_q\left(\frac{M}{\sqrt{s}} e^{-Y}\right) \tilde{f}_{\bar{q}}\left(\frac{M}{\sqrt{s}} e^{Y}\right) \hat{F}_k(M, -z)\right], \quad (8)$$

which are defined correspondingly to (1). The plots of the $F_k(M, Y, z)$ z-dependence at fixed M, Y are shown in Figs. 3(a–g) of Appendix A. For small invariant masses ($M < 100$–120 GeV), the F_3 and F_4 functions are almost symmetric and therefore are suppressed in A_{FB}. This observation leads to the idea that only the two first terms in (7) are dominant for the asymmetry. However, such behavior does not persist for more heavy M bins ($M > 100$–120 GeV). As we see in Figs. 3(e–g), in this case the F_3 and F_4 functions demonstrate behavior that significantly contributes to the asymmetry. So the number of the unknown functions cannot be reduced for heavy invariant masses. Nevertheless, the A_{FB} remains a convenient observable because it is very sensitive to the small changes of the coupling values everywhere. Thus, to analyze the A_{FB}, we preserve in the cross section $\frac{d^3\sigma}{dMdYdz}$ all the terms entering (7).

Next, it is important to notice that the CMS detector has a finite acceptance and only the leptons with $p_T > p_0 = 20$ GeV can be detected. Therefore, to obtain the cross section of interest we have to integrate the distributions over z in the interval $-z_0$ to $+z_0$, where

$$z_0 = \sqrt{1 - 4p_0^2/M^2}. \tag{9}$$

III. ESTIMATION OF Z' COUPLINGS

The forward-backward asymmetry is defined as

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}, \tag{10}$$

where

$$\sigma_F = \int_0^{z_0} \frac{d\sigma}{dz} dz, \qquad \sigma_B = \int_{-z_0}^{0} \frac{d\sigma}{dz} dz \tag{11}$$

and z_0 is given in (9). Providing the notations

$$\Delta = \sigma_F - \sigma_B, \qquad \Sigma = \sigma_F + \sigma_B, \tag{12}$$

we can rewrite (10) in terms of the Z' contributions,

$$A_{FB}(M, Y) = \frac{\Delta(M, Y)}{\Sigma(M, Y)} = \frac{\Delta^{\mathrm{SM}} + \bar{a}^2\Delta_1 + \bar{a}\bar{v}_l\Delta_2 + \bar{a}\bar{v}_u\Delta_3 + \bar{v}_l\bar{v}_u\Delta_4}{\Sigma^{\mathrm{SM}} + \bar{a}^2\Sigma_1 + \bar{a}\bar{v}_l\Sigma_2 + \bar{a}\bar{v}_u\Sigma_3 + \bar{v}_l\bar{v}_u\Sigma_4}, \tag{13}$$

where, according to (8),

$$\Delta_k(M, Y) = \int_0^{z_0} F_k(M, Y, z)dz - \int_{-z_0}^{0} F_k(M, Y, z)dz,$$

$$\Sigma_k(M, Y) = \int_0^{z_0} F_k(M, Y, z)dz + \int_{-z_0}^{0} F_k(M, Y, z)dz.$$

Expression (13) is used for fitting the Z' parameters.

We calculate Σ^{SM} by means of FEWZ 3 [19] and A_{FB}^{SM}, Δ^{SM}, $\Delta_{1,2}$, and $\Sigma_{1,2}$ by using Wolfram *Mathematica* 10 [20], FeynArts, and FormCalc [21]. Some of computations were fulfilled at the Dubna cluster HybriLIT [22]. The accuracy of all these calculations is considered in detail in the discussion.

The results of the carried out calculations are presented in Table I. They demonstrate at almost 2σ C.L. that the data on the A_{FB} at $\sqrt{s} = 7$ and 8 TeV are compatible with the Z' existence. The corresponding graphical representation of these results are shown in Figs. 1 and 2. The estimates of all the Z' couplings to the SM fermions are obtained. The values of parameters $\bar{a}\bar{v}_l$ and $\bar{a}\bar{v}_u$ are found as independent variables first in the literature.

TABLE I. The C.L. intervals for the Z' couplings.

$m_{Z'}$, GeV	92% C.L. boundaries, 7 TeV	92% C.L. boundaries, 8 TeV
1200	$\bar{a}^2 = (1.5^{+36.5}_{-1.4}) \times 10^{-5}$	$\bar{a}^2 = (1.3^{+20.8}_{-1.2}) \times 10^{-5}$
	$\bar{a}\bar{v}_l = (-0.4^{+3.8}_{-3.8}) \times 10^{-5}$	$\bar{a}\bar{v}_l = (-0.2^{+5.5}_{-14.2}) \times 10^{-5}$
	$\bar{a}\bar{v}_u = (3.4^{+4.2}_{-3.0}) \times 10^{-3}$	$\bar{a}\bar{v}_u = (3.4^{+1.7}_{-1.8}) \times 10^{-3}$
3000	$\bar{a}^2 = (2.3^{+38.7}_{-1.2}) \times 10^{-5}$	$\bar{a}^2 = (1.3^{+20.9}_{-1.2}) \times 10^{-5}$
	$\bar{a}\bar{v}_l = (-0.6^{+6.7}_{-0.8}) \times 10^{-5}$	$\bar{a}\bar{v}_l = (-0.2^{+5.5}_{-14.1}) \times 10^{-5}$
	$\bar{a}\bar{v}_u = (4.0^{+3.6}_{-3.6}) \times 10^{-3}$	$\bar{a}\bar{v}_u = (3.4^{+1.7}_{-1.8}) \times 10^{-3}$
3500	$\bar{a}^2 = (2.4^{+38.6}_{-1.3}) \times 10^{-5}$	$\bar{a}^2 = (1.3^{+20.9}_{-1.2}) \times 10^{-5}$
	$\bar{a}\bar{v}_l = (-0.6^{+6.8}_{-0.8}) \times 10^{-5}$	$\bar{a}\bar{v}_l = (-0.2^{+5.5}_{-14.1}) \times 10^{-5}$
	$\bar{a}\bar{v}_u = (4.0^{+3.6}_{-3.6}) \times 10^{-3}$	$\bar{a}\bar{v}_u = (3.4^{+1.7}_{-1.8}) \times 10^{-3}$
4000	$\bar{a}^2 = (2.4^{+38.6}_{-1.3}) \times 10^{-5}$	$\bar{a}^2 = (1.3^{+20.9}_{-1.2}) \times 10^{-5}$
	$\bar{a}\bar{v}_l = (-0.6^{+6.9}_{-0.8}) \times 10^{-5}$	$\bar{a}\bar{v}_l = (-0.2^{+5.5}_{-14.1}) \times 10^{-5}$
	$\bar{a}\bar{v}_u = (4.0^{+3.6}_{-3.6}) \times 10^{-3}$	$\bar{a}\bar{v}_u = (3.4^{+1.7}_{-1.8}) \times 10^{-3}$
4500	$\bar{a}^2 = (2.4^{+38.6}_{-1.3}) \times 10^{-5}$	$\bar{a}^2 = (1.3^{+20.9}_{-1.2}) \times 10^{-5}$
	$\bar{a}\bar{v}_l = (-0.6^{+6.8}_{-0.8}) \times 10^{-5}$	$\bar{a}\bar{v}_l = (-0.2^{+5.5}_{-14.1}) \times 10^{-5}$
	$\bar{a}\bar{v}_u = (4.0^{+3.6}_{-3.6}) \times 10^{-3}$	$\bar{a}\bar{v}_u = (3.4^{+1.7}_{-1.8}) \times 10^{-3}$

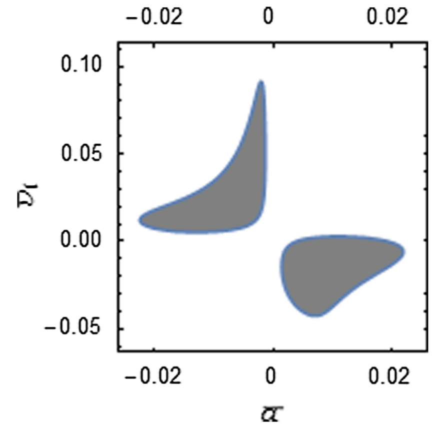

FIG. 1. The 92% C.L. area for the Z' couplings: $(\bar{a}, \bar{v}_l)$ plane at $m_{Z'} = 3$ TeV, $\bar{v}_u = 5 \times 10^{-2}$.

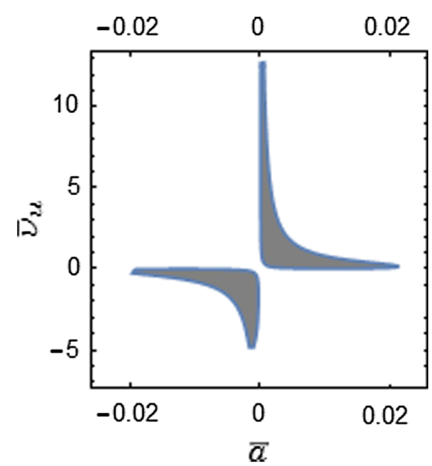

FIG. 2. The 92% C.L. area for the Z' couplings: $(\bar{a}, \bar{v}_q)$ plane at $m_{Z'} = 3$ TeV, $\bar{v}_l = 5 \times 10^{-4}$.

IV. DISCUSSION

We have analyzed the data on the A_{FB} for the Drell-Yan annihilation process at the LHC presented by the CMS collaborations for $\sqrt{s} = 7$ [12] and 8 TeV [13] with the goal of estimating in a model-independent approach the couplings of the Abelian Z' boson to the SM fermions. The investigation was carried out within the effective Lagrangian (2) and (3). As the important ingredient the relations (5) were used. They essentially decreased the number of couplings, which must be fitted, and modified accordingly the kinematics structure of the cross sections. As a result, the angular distribution of the theoretic cross section became uniquely determined by this particle. It is important to note that the relations are satisfied at tree level in all the extended models investigated by the CMS and ATLAS [23–24] collaborations in the model-dependent approach. They also cover other renormalizable models of Abelian Z' [9]. Because of these constraints, we performed the three-parametric fit of the experimental data and estimated the unknown $\bar{a}^2$, $\bar{a}\bar{v}_l$, and $\bar{a}\bar{v}_u$ couplings for a number of $m_{Z'}$.

The maximum likelihood method was applied. The QCD sector was evaluated with a next-to-next-to-leading order accuracy, while the electroweak corrections were calculated up to next-to-leading order (NLO). This is a standard for the Drell-Yan production description at the LHC nowadays. The NLO effects are accounted for by means of an improved Born approximation (IBA). As it is known, the IBA absorbs the majority of NLO electroweak corrections. It is shown in [25] that its deviation from exact NLO calculations does not exceed 1%–2%. In the IBA approach, the coupling constants are replaced with the effective running couplings, which are obtained from the one-loop expressions for the self-energy and vertex corrections. In fact, it means that we use an elastic scattering approximation but in all calculations we replace $\alpha_{em}(0)$ with $\alpha_{em}(m_Z)$. The PDF uncertainties were estimated by means of the standard formula (see, for example, [26])

$$\Delta F = \frac{1}{2}\sqrt{\sum_{k=1}^{n}[F(S_k^+) - F(S_k^-)]^2}, \quad (14)$$

where F is any quantity that depends on PDFs, $S_k^\pm$ are the PDF eigenvectors, and summation is performed over all the eigenvectors present in a given PDF set. In Table II, we show the example for Σ_k factors in the bin $86 \le M \le 96$, $0 \le |Y| \le 1$. From the presented results we see that the PDF uncertainty of the Z' cross sections does not exceed 3%. Finally, considering all the discussed uncertainties as independent, we obtain that the total theoretical uncertainty of the A_{FB} predicted by (13) is not larger than 5%.

The uncertainties following from the statistical and the PDF errors were calculated at $\sim 2\sigma$ C.L. It was concluded that the Z' existence is admitted by the data on A_{FB} measured by the CMS at $\sqrt{s} = 7$ and 8 TeV. The Z' signal (hint, in fact) is nonzero at 92% C.L. The obtained numerical values for the Z' coupling $\bar{v}_l^2$ are in agreement with the ones found already for the LEP [9] and Tevatron [27] in a model-independent analysis where other observables were proposed.

It is worth noting that the $\bar{a}\bar{v}_l$ coupling and $\bar{a}\bar{v}_u$ were estimated directly for the first time. In all other previous analyses only $\bar{v}_l^2$ could be estimated, while $\bar{a}\bar{v}_l$ was suppressed due to the process kinematics. Let us compare those values with our results. The calculation yields $\bar{v}_l^2 < 2.8 \times 10^{-4}$ which is in agreement with $\bar{v}_l^2 = (2.25^{+1.79}_{-2.07}) \times 10^{-4}$ from [9] and $\bar{v}_l^2 < 1.69 \times 10^{-4}$ from [27]. Further, as we see from Table I, the experimental CMS data at 7 and 8 TeV, which were obtained with different precision, lead to the close values for estimated parameters.

It is essential that the obtained coupling values are weakly dependent on the Z' mass. It is caused by the cross-section dependence on this parameter. Really, the factors $\hat{F}_{qk}$ in Eq. (7) depend on the $m_{Z'}$ through the Z' propagator. This is a denominator effect, which is small at the energies that are not close to the Z' pole position. On the contrary, the couplings enter the cross section through the numerator. Hence, the observables are much more sensitive to the coupling variations.

Now let us turn back to Eq. (4). The current limit on the Z–Z' mixing angle from the global fit of the LEP data is about $|\theta_0| = 10^{-3}$–10^{-4}. We use this value to estimate the $m_{Z'}$. Because of (4), θ_0 is expressed through $\bar{a}$ and $m_{Z'}$. Since $\bar{a}$ is already derived, it is possible to obtain the $m_{Z'}$ limits that satisfy the LEP restrictions on θ_0. The optimistic estimation is $3 < m_{Z'} < 7$–8 TeV. The experimental lower limit was recently increased to the $m_{Z'} > 3.5$ TeV in the model-dependent analysis presented by the CMS and ATLAS collaborations. It will be possible to detect Z' with such mass in the future LHC experiments. Nevertheless, in this case it is difficult to distinguish the basic Z' model. Therefore, the model-independent description becomes an important instrument for investigating this problem. The obtained values of the couplings could be used in the Z' model identifications either at present or future colliders.

Finally, we compare our results for $\bar{a}^2$ with those of [9] and [27], where the data of the LEP and some LHC experiments have been analyzed on the same principles as in the present paper. The essential difference, however, is that in the former case it was possible to introduce a one-parameter observable for estimating the $\bar{a}^2$. The $\bar{a}\,\bar{v}_l$ contribution was excluded due to more simple kinematics structure of the lepton cross sections for the processes $e^+e^- \to \mu^+\mu^-(\tau^+\tau^-)$. The $\bar{a}^2$ found in [9] has the value $\bar{a}^2 \le 0.95 \times 10^{-3}$ that differs from our result $\bar{a}^2 = (2.4^{+38.6}_{-1.3}) \times 10^{-5}$. This is a universal parameter related due to (4) with the $Z - Z'$ mixing angle, which was estimated at LEP experiments [15]. On the contrary, the value of $\bar{a}^2$ found in [27] is one order larger than that obtained in Sec. III. We could explain this discrepancy by the approximation for the Drell-Yan process cross section used in [27], which is applicable at energies close to the resonance peak only. Possibly, this also depends on the data set and observables introduced in the course of the analysis applied.

In conclusion we note that the applied model-independent approach can be used for analyzing data of other experiments. In fact, at the LHC numerous data on different processes have been accumulated. Further improvements of the results are expected from measurements fulfilled at run 2 of the LHC. So it is of interest to investigate these measurements by the applied method. Besides that, the Z-boson production is attractive where the Z–Z' mixing angle θ_0 can be estimated and compared with the one obtained in the present paper. We left all these problems for the future.

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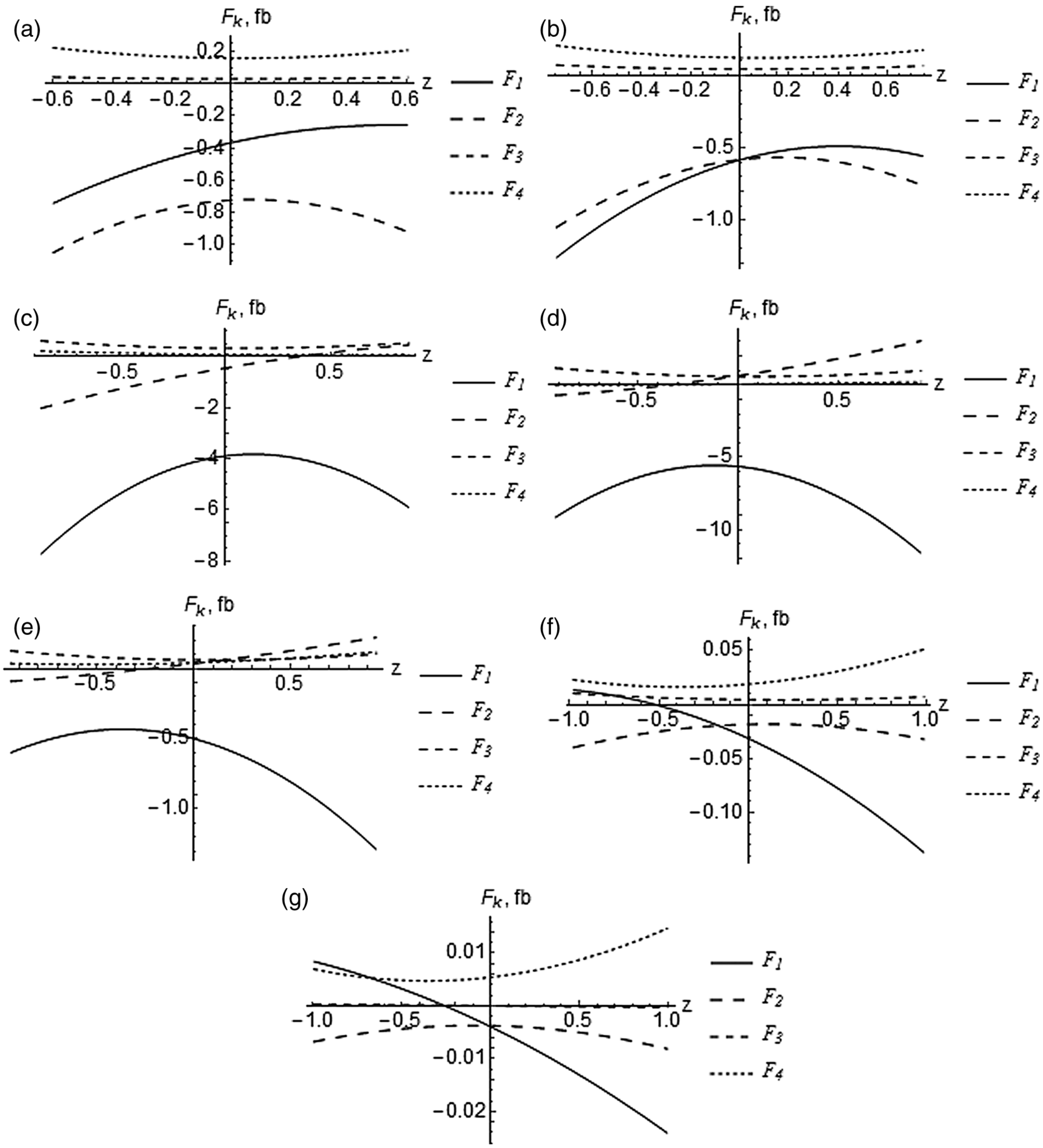

FIG. 3. (a) $F_k(M, Y, z)$ factors at $M = 50$ GeV, $Y = 1.25$. (b) $F_k(M, Y, z)$ factors at $M=60$ GeV, $Y=1.25$. (c) $F_k(M, Y, z)$ factors at $M = 80$ GeV, $Y = 1.25$. (d) $F_k(M, Y, z)$ factors at $M=100$ GeV, $Y=1.25$. (e) $F_k(M, Y, z)$ factors at $M = 120$ GeV, $Y = 1.25$. (f) $F_k(M, Y, z)$ factors at $M = 200$ GeV, $Y = 1.25$. (g) $F_k(M, Y, z)$ factors at $M = 400$ GeV, $Y = 1.25$.

APPENDIX A: THE PLOTS OF THE Z' FACTORS

Below we present the behavior of the cross-section factors introduced in (7) and (8). Here the functions F_1, F_2, F_3, and F_4 stand for the factors at $\bar{a}^2$, $\bar{a}\bar{v}_l$, $\bar{a}\bar{v}_u$, and $\bar{v}_l\bar{v}_u$, respectively.

APPENDIX B: ON THE RELATION BETWEEN THE Z' COUPLINGS

Below we adduce information on the derivation of mixing angle (4) and correlations (5). As was noted in Sec. II, these correlations are proper to renormalizable models containing the Abelian Z' boson. They have been obtained in [10] and [11] by using two different procedures (see [9] for details). The general idea of the first approach is mentioned in the main text. The second way is based on the principle of gauge invariance with respect to the $\tilde{U}(1)$ transformations [11].

The most general effective Lagrangian describing the Z' interactions with the SM fields and preserving the $SU(2)_L \times U(1)_Y \times \tilde{U}(1)$ gauge group reads [17–18]

$$\mathcal{L} = \frac{1}{2}|(iD^{ew,\phi}_\mu + \tilde{g}\tilde{Y}_\phi Z'_{0\mu})\phi|^2 + \sum_{f_L}\bar{f}_L(iD^{ew,L}_\mu + \tilde{g}\tilde{Y}^L_f Z'_{0\mu})\gamma^\mu f_L + \sum_{f_R}\bar{f}_R(iD^{ew,R}_\mu + \tilde{g}\tilde{Y}^R_f Z'_{0\mu})\gamma^\mu f_R, \quad \text{(B1)}$$

where the summation over all the SM left-handed doublets, f_L, and the SM right-handed singlets, f_R, is assumed and $D^{ew,L}_\mu = \partial_\mu - \frac{ig}{2}\sigma^a A^a_\mu - \frac{ig'}{2}Y_{f,L}B_\mu$ is the standard model covariant derivative with the values of the hypercharges: $Y_\phi = 1$, $Y_{f,L} = \frac{1}{3}$, and $D^{ew,R}_\mu = \partial_\mu - ig'Q_f B_\mu$, Q_f is the fermion charge in the positron charge units, and σ^a are the Pauli matrices. The values of the dimensionless constants $\tilde{Y}_\phi$, $\tilde{Y}^L_f$. $\tilde{Y}^R_f$ depend on a particular model and here are considered as arbitrary numbers.

The masses of the SM particles are generated by the spontaneous breaking of the $SU(2)_L \times U(1)_Y \to U(1)_{em}$ symmetry due to the nonzero vacuum value of the scalar doublet. Hence, the mass eigenstates of the vector bosons appeared to be shifted from the original fields A^a_μ, B_μ, $Z'_{0\mu}$ because the corresponding mass matrix became nondiagonal. Physical fields A_μ, Z_μ, Z'_μ are obtained by the orthogonal transformation,

$$B_\mu = A_\mu c_W - (Z_\mu c_0 - Z'_\mu s_0)s_W,$$
$$A^3_\mu = A_\mu s_W + (Z_\mu c_0 - Z'_\mu s_0)c_W,$$
$$Z'_{0\mu} = Z_\mu s_0 + Z'_\mu c_0, \quad \text{(B2)}$$

where $c_W = \cos\theta_W$, $s_W = \sin\theta_W$, and the SM value of the Weinberg angle $\tan\theta_W = g'/g$; whereas $c_0 = \cos\theta_0$, $s_0 = \sin\theta_0$ denote the cosine and sine of the mixing angle θ_0 relating the physical states Z_μ, Z'_μ to the massive neutral components of the $SU(2)_L \times U(1)_Y \times \tilde{U}(1)$ gauge fields. The value of the θ_0 can be determined from the relation

$$\tan^2\theta_0 = \frac{m^2_W/c^2_W - m^2_Z}{m^2_{Z'} - m^2_W/c^2_W}, \quad \text{(B3)}$$

(see also [17]) expressing it through the masses of physical states, which appeared after the orthogonalization, and the SM Weinberg angle. The difference in the numerator of the rhs is positive and completely determined by the Z' coupling to the scalar field doublet [11]. After the diagonalization, the masses of physical states are given by

$$m^2_A = 0,$$
$$m^2_Z = m^2_W c^{-2}_W\left(1 - \frac{4\tilde{g}^2\tilde{Y}^2_\phi}{g^2}\frac{m^2_W}{m^2_{Z'} - m^2_W c^{-2}_W}\right),$$
$$m^2_{Z'} = m^2_{Z'_0} + (m^2_W c^{-2}_W - m^2_Z) + \frac{4\tilde{g}^2\tilde{Y}^2_\phi}{g^2}m^2_W. \quad \text{(B4)}$$

Here, $m_{Z'_0}$ is the mass of the Z' before diagonalization. This value is not specified and is a free parameter. As we see, the mass m_Z differs from the SM value m_W/c_W by a small quantity of the order $\sim m^2_W/m^2_{Z'}$. So the mixing angle (B3) is also small, $\theta_0 \sim m^2_W/m^2_{Z'}$. Using (B2) the Lagrangian of the model can be expressed in terms of the physical fields. The θ_0-dependent terms generate new interactions originally absent in (B1). Here it worth recalling that in calculations carried out we used the SM value of the Weinberg angle $\tan\theta_W = g'/g$.

To derive the correlations (5) we require the Yukawa terms of the SM to be invariant with respect to the $\tilde{U}(1)$ gauge symmetry. This condition is fulfilled if the relation holds,

$$\tilde{Y}^R_f = \tilde{Y}^L_f + 2T^3_f\tilde{Y}_\phi. \quad \text{(B5)}$$

Introducing the Z' interaction constants with the vector and axial-vector currents of fermions $v^f_{Z'} = \frac{\tilde{g}}{2}(\tilde{Y}^L_f + \tilde{Y}^R_f)$, $a^f_{Z'} = \frac{\tilde{g}}{2}(\tilde{Y}^L_f - \tilde{Y}^R_f)$, we can rewrite (B5) in the form (5). These correlations also hold in two-Higgs-doublets SM [10] and [9].

The relation (B5) is just as in the SM for the given proper values of the hypercharges Y^R_f, Y^L_f, Y_ϕ. In the extended models, the originally independent parameters $\tilde{Y}^R_f$, $\tilde{Y}^L_f$, $\tilde{Y}_\phi$ have to be connected ones. The fermion and the scalar sectors of the Z' physics are correlated. In particular, the mixing angle is simply related with the universal axial-vector coupling a^2_f.

APPENDIX C: PDF UNCERTAINTIES

In this appendix, we present a table that illustrates the calculation of the PDF uncertainties with Eq. (14). It shows the Z' factors Σ_k integrated over the bin $86 \le M \le 96$, $0 \le |Y| \le 1$ with some of the PDF eigenvectors,

$$\Sigma_k = \int_{86GeV}^{96GeV} dM \int_{-1}^{1} dY \Sigma_k(M, Y).$$

$\Sigma_k(M, Y)$ are defined in (12), and $\langle\Sigma\rangle$ means the central values.

TABLE II. The Z' factors calculated with different PDF eigenvectors and integrated over $86 \le M \le 96$, $0 \le |Y| \le 1$.

	Σ_1, pb	Σ_2, pb	Σ_3, pb	Σ_4, pb
1	−3366.02	200.44	205.64	1.96
2	−3364.16	200.31	205.59	1.96
3	−3364.55	200.50	207.17	1.95
4	−3365.51	200.27	204.30	1.97
5	−3373.87	200.62	207.58	1.98
6	−3358.97	200.21	204.23	1.96
7	−3369.25	200.91	206.24	1.97
8	−3362.64	200.06	205.23	1.96
9	−3414.86	203.46	208.02	2.00
10	−3323.79	197.83	203.62	1.94
11	−3362.33	200.58	210.16	1.94
12	−3365.90	200.28	203.90	1.97
13	−3350.05	199.40	204.09	1.95
14	−3374.68	201.01	206.62	1.97
15	−3359.04	200.06	205.05	1.96
16	−3354.31	199.71	205.13	1.96
17	−3366.81	200.26	206.29	1.97
18	−3361.63	200.50	204.53	1.96
19	−3360.79	200.18	205.07	1.96
20	−3345.18	199.14	204.75	1.95
$\langle\Sigma\rangle$, pb	−3365.09	200.37	205.61	1.96
$\frac{\Delta\Sigma}{\langle\Sigma\rangle}$, %	1.6	1.4	2.6	2.1

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