Model-independent constraints on the Abelian $Z'$ couplings within the ATLAS data on the dilepton production processes at $\sqrt{s} = 13$ TeV

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The study of lepton pair production is a powerful test of the Standard Model (SM) and can be used to search for phenomena beyond the SM. New heavy neutral bosons $Z'$ decaying to charged lepton pairs $l^{+} l^{-} \ (l = e, \mu)$ are predicted by many scenarios of new physics, including models with extended gauge sector. We estimate the LHC $Z'$ discovery potential with Run 2 data comprised of 36.1 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV and recorded by ATLAS detector at the CERN LHC. The model-independent constraints on the $Z'$ fermion couplings were obtained for the first time for a selected set of $Z'$ signal mass points of $M_{Z'} = 2, 3, \text{ and } 4$ TeV by using the ATLAS data collected at the LHC. The analysis is based on the derived earlier special relations between the $Z'$ couplings proper to the renormalizable theories. Taking into account the dependence of $Z - Z'$ mixing angle $\theta_0$ on the $Z'$ axial-vector coupling $a$, the limits on $\theta_0$ are established as $\theta_0 < 10^{-4} - 10^{-3}$ in the investigated $Z'$ mass range.

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I. INTRODUCTION

Variety of new physics (NP) scenarios beyond the SM, including superstring and left-right-symmetric models, predict the existence of new neutral $Z'$ gauge bosons, which might be light enough to be accessible at current and/or future colliders [1–4]. The search for these new neutral $Z'$ gauge bosons is an important aspect of the experimental physics program of current and future high-energy colliders. Present limits from direct production at the LHC and virtual (indirect) $Z'$ bounds at LEP, through interference with the $Z$ boson, imply that new $Z'$ bosons are rather heavy. Depending on the considered theoretical models, the current limits on $Z'$ masses from their direct search at the LHC at 13 TeV are of the order of 3.7–4.5 TeV [5, 6]. Another important dynamical characteristic of the $Z'$ bosons is the $Z - Z'$ mixing angle which is strongly constrained by the ATLAS and CMS data in the diboson channel [7, 8]. The diboson decay modes of $Z'$ directly probe the gauge coupling strength between the new and the SM gauge bosons.

Among the extensions of the SM at the TeV scale, those with an additional $\tilde{U}(1)$ factor in the gauge group, associated with a heavy neutral gauge boson $Z'$, have often been considered in direct and indirect searches for new physics, and in the studies of possible early and current discoveries at the LHC [9]. Many varieties of $Z'$ models have been considered over the years [10–16]. From now on, we will concentrate on a class of Abelian $Z'$ models, previously discussed in [10–16].

By Abelian $Z'$ models we mean the $\tilde{U}(1)$ extensions of the SM. We assume also that the model contains
(i) no exotic vectors, apart from a single $Z'$ associated with an extra $\tilde{U}(1)$ factor in the gauge group, commuting with $SU(3)_C \times SU(2)_L \times U(1)_Y$, and
(ii) no exotic fermions. Abelian class of $Z'$ models interpolates continuously among several discrete examples already considered in the literature such as the $Z'_1$ model arising from $SO(10)$ unification, left-right symmetric models, etc.

This class of the Abelian $Z'$ models is motivated to emerge as a natural benchmark for comparing direct and indirect signals in different experimental contexts in particular for organizing experimental searches at the LHC [17, 18]. Nevertheless, the model-dependent $Z'$ analysis may have some difficulties in the nearest future. The identification reach for the majority of the models is about the current estimated lower bound of the $Z'$ mass. This means it will be problematic to distinguish the basic $Z'$ model even if the $Z'$ is discovered experimentally.

In such a situation, a model-independent approach is also very perspective. In contrast to the model-dependent searches for the $Z'$ boson at the LHC where only one free parameter exists (the mass of the $Z'$) for a given $Z'$ model, in model-independent approach all fermion coupling constants are considered as free parameters. Therefore, model-independent approaches are
prospective for estimating not only the mass but also \(Z'\) couplings to the SM particles. As a result, definite classes of the extended models could be restricted. The obvious shortcoming of model-independent searches is a sufficiently large amount of free parameters which must be fitted in experiments. However, it can be reduced if some natural requirements or theoretical arguments are imposed. For example, the considered Abelian \(Z'\) boson assumes that the extended model is a renormalizable one. This property results in a series of specific relations between couplings called in what follows the renormalization group relations (RGR), that reduces the number of unknown parameters essentially. The \(Z–Z'\) mixing angle becomes also a self-consistent part of the parametric space. RGR lead to the kinematical structure of the differential cross sections allowing picking out uniquely the Abelian \(Z'\) between other spin-1 neutral particles. In the Abelian class of \(Z'\) models, the main \(Z'\) properties and its couplings to the SM states can be completely described in terms of three independent fermion couplings and the \(Z'\) mass, \(M_{Z'}\).

As we will see below, the parameterization of the Abelian \(Z'\) boson is a kind of model-independent study, which does not specify numeric values of the \(Z'\) couplings and automatically takes into account \(Z–Z'\) mixing effects. Such an approach was developed in \[10–16\]. In these investigations, the mixing angle, the couplings of the \(Z'\) to axial and vector lepton and quark currents, as well as to Higgs field, and the mass \(M_{Z'}\), have been estimated at \(1\sigma–2\sigma\) C.L. mainly at non-resonant energies. In the off-resonance case the cross section is dominated by the interference of the SM and the \(Z'\) parts in the scattering amplitude. In this regime, the width of the \(Z'\) boson is not very essential.

In all the model-dependent searches fulfilled at the LHC the narrow width approximation has been applied. It implies that the ratio of the resonance width \(\Gamma_{Z'}\) to the \(Z'\) mass should be small, \(\Gamma_{Z'}/M_{Z'} \lesssim 3\%\). This value is typical for the couplings in the usually considered models. In this case, the interference term in the cross-section is suppressed and the cross section can be approximated as the product of the \(Z'\) production cross section and the \(Z'\) decay branchings into the SM particles.

Since the different terms of the cross sections are dominant in these two ways of data treating, it is of interest to estimate the parameters of the \(Z'\) in the model-independent approach and the direct search method for the Drell-Yan process within data accumulated at \(\sqrt{s} = 13\text{ TeV}\). Then it is interesting to compare them with the ones obtained already in \[10, 12\] at \(\sqrt{s} = 7, 8\text{ TeV}\) in the indirect search technique. This is the goal of the present paper.

In this work, we derive model-independent bounds on the fermion \(Z'\) coupling constants in dilepton production process

\[ p + p \rightarrow Z' \rightarrow l^+l^- + X \]  

\((l = e, \mu)\) from the available ATLAS data at the LHC at \(\sqrt{s} = 13\text{ TeV}\). We will show that the use of a model-independent parameterization, such as the one suggested in present work, is a valuable tool to systematically organize the \(Z'\) searches.

The paper is organized as follows. In the next section, the information on the RGR necessary for what follows is given and the effective Lagrangian describing interaction of the \(Z'\) with the SM particles is adduced. Finally, in the Section 3, the results of the \(Z'\) couplings estimates are introduced and further are compared with some previous known results in the Discussion.

## II. EFFECTIVE LAGRANGIAN AND RGR RELATIONS

The effective low energy Lagrangian describing the interaction of the \(Z\) and \(Z'\) mass eigenstates can be written as (see, e.g. \[10\]):

\[ L_{Zff} = Z_{\mu} f_{\mu} [(v_f^{SM} + \gamma f_{SM}^{Z}) \cos \theta_0 + (v_f + \gamma a_f) \sin \theta_0] f, \]

\[ (2) \]

\[ L_{Z'ff} = Z'_{\mu} f_{\mu} [(v_f + \gamma a_f) \cos \theta_0 - (v_f^{SM} + \gamma a_f^{SM}) \sin \theta_0] f, \]

\[ (3) \]

where \(f\) is an arbitrary SM fermion state; \(v_f^{SM}, a_f^{SM}\) are the SM axial-vector and vector couplings of the \(Z\)-boson, \(a_f\) and \(v_f\) are the ones for the \(Z'\), \(\theta_0\) is the \(Z–Z'\) mixing angle. The definitions here are such that

\[ v_f^{SM} = (T_{3f} - 2Q_f s_W^2)/(2s_W c_W), \]

\[ a_f^{SM} = -T_{3f}/(2s_W c_W). \]

\[ (4) \]

In what follows, we will also use the “normalized” couplings,

\[ \bar{a}_f \equiv \frac{1}{\sqrt{4\pi M_{Z'}}} M_{Z'} a_f, \quad \bar{v}_f \equiv \frac{1}{\sqrt{4\pi M_{Z'}}} M_{Z'} v_f. \]

\[ (5) \]

Within the considered formulation, this angle is determined by the coupling \(Y_\phi\) of fermions to the scalar field as follows (see \[10\] and Appendix B of \[16\] for details)

\[ \theta_0 = \frac{\bar{g} \sin \theta_W \cos \theta_W M_Z^2}{\sqrt{4\pi \alpha_{em}} M_{Z'}^2 Y_\phi + O \left( \frac{M_Z^2}{M_{Z'}^2} \right). \]

\[ (6) \]

where \(\theta_W\) is the SM Weinberg angle, \(\bar{g}\) is \(\bar{U}(1)\) gauge coupling constant and \(\alpha_{em}\) is the electromagnetic fine structure constant. Although \(\theta_0\) is small quantity of order \((m_{Z'}^2/m_Z^2)\), it contributes to the \(Z\) and \(Z'\) bosons exchange amplitudes and cannot be neglected.

As was shown in \[10, 11\], if the extended model is renormalizable and contains the SM as a subgroup, the relations between the couplings hold:

\[ v_f - a_f = v_{f'}, a_f = T_{3f} \bar{g} Y_\phi. \]

\[ (7) \]
Here $f$ and $f^*$ are the partners of the $SU(2)_L$ fermion doublet ($l^* = \nu, \nu^* = \bar{l}, q^*_u = q_d$ and $q^*_d = q_u$), $T_3^f$ is the third component of the weak isospin. These relations are proper to the models of the Abelian $Z'$. They are just as the correlations for the special values of the hypercharges $Y^f_1, Y^f_2, Y_\phi$ of the left-handed, right-handed fermions, and scalars in the SM. But now these parameters are some arbitrary numbers.

The correlations (7) have been already derived in two different ways. The first one originates from the structure of the renormalization group operator and other one is founded on the requirement of the SM Yukawa term invariance with respect to the additional $U(1)$ group.

From now on we will assume that the axial-vector coupling $a_f$ is universal, so that

$$a \equiv a_e = -a_u = a_d = -a_u = ... \quad (8)$$

Being combined with Eqs. (6) and (7), it yields

$$\theta_0 = -2a \frac{\sin \theta_W \cos \theta_W}{\sqrt{4 \pi \alpha_{em}}} \frac{M_f^2}{M_Z^2} + O \left( \frac{M_f^4}{M_Z^6} \right). \quad (9)$$

Eq. (7) plays crucial role in what follows. First, due to the number of independent parameters is considerably reduced. Second (but not less important) is influence on kinematics of scattering processes. If the signal is observed, due to these relations of Eq. (7) one can guarantee that exactly the Abelian $Z'$ state is observed. Finally, it is important to notice that the relations (7) hold also in the Two-Higgs-Doublet Model (THDM). All this makes the direct searching for the $Z'$ combined with (7) grounded and perspective.

### III. NUMERICAL ANALYSIS AND CONSTRAINTS ON $Z'$ COUPLINGS

The differential cross section for $Z'$ production in the process (11) from initial quark-antiquark states can be written as

$$\frac{d^2 \sigma^{Z'}}{dM_{ll} \, dY} = K \frac{2M_{ll}}{s} \times$$

$$\times \sum_q \left[ f_{q\bar{q}} p_1(\xi_1) f_{\bar{q}q} p_2(\xi_2) + \left\{ q \leftrightarrow \bar{q} \right\} \frac{d^2 \sigma^{Z'}}{dY} \right]. \quad (10)$$

Here, $s$ denotes the proton-proton center-of-mass energy squared, $z \equiv \cos \theta$, with $\theta$ the $l^+l^-$ quark in the $l^+l^-$ center-of-mass frame and $Y$ is the dilepton rapidity. Furthermore, $f_{q\bar{q}} p_1(\xi_1, M_{ll})$ and $f_{\bar{q}q} p_2(\xi_2, M_{ll})$ are parton distribution functions for the protons $P_1$ and $P_2$, respectively, with $\xi_{1,2} = (M_{ll}/s)^{\frac{1}{2}} \exp(\pm Y)$ the parton fractional momenta. Finally, $d^2 \sigma^{Z'}/dz$ are the partonic differential cross sections. In (11), the $K$ factor (=1.3) accounts for higher-order QCD contributions and we use improved Born approximation for EW part [10]. For numerical computation, we use MSTW PDF sets [20].

The cross section for the narrow $Z'$ state production and subsequent decay into a $l^+l^-$ pair needed in order to estimate the expected number of $Z'$ events, $N_{ll}^{Z'}$, is derived from (11) by integrating the right-hand-side over $z$, over the rapidity of the $l^+l^-$ pair and invariant mass $M_{ll}$ around the resonance peak $(M_{Z'} - \delta M_{ll}/2, M_{Z'} + \delta M_{ll}/2)$:

$$\sigma^{Z'}(pp \to l^+l^- + X) = \int_{M_{Z'} - \delta M_{ll}/2}^{M_{Z'} + \delta M_{ll}/2} dM_{ll} \times (11)$$

$$\times \int_{-Y}^Y dY \int_{z_{cut}}^{z_{cut}} dz \frac{d^2 \sigma^{Z'}}{dM_{ll} \, dY \, dz},$$

where the phase space can be found, e.g. in [21]. Here, $\Delta M_{ll}$ being the mass window. Notice, that in all the cases studied, the true width of the resonance $\Gamma_{Z'}$ is smaller than the Gaussian experimental resolution $\Gamma_m$.

For each mass point, having determined the observed resonance width $\Delta m$, a mass window $\Delta M_{ll}$ can be defined as $\pm 3\Delta m$ around the $Z'$ mass [21].

Using Eq. (12), the number of signal events for a narrow $Z'$ resonance state can be written as follows

$$N^{Z'} = L \cdot \epsilon \cdot \sigma^{Z'}(pp \to l^+l^- + X) \equiv (12)$$

$$\epsilon \equiv L \cdot \epsilon \cdot A_{ll} \cdot \sigma(pp \to Z') \cdot B(Z' \to l^+l^-).$$

Here, $L$ denotes the integrated luminosity, and the overall kinematic and geometric acceptance times trigger, reconstruction and selection efficiencies, $A_{ll} \times \epsilon$, is defined as the number of signal events passing the full event selection divided by the number of generated events. Finally, $\sigma(pp \to Z') \times B(Z' \to l^+l^-)$ is the (theoretical) total production cross section times branching ratio extrapolated to the total phase space. Finally, $B(Z' \to l^+l^-) = \Gamma(Z' \to l^+l^-)/\Gamma_{Z'}$, where $\Gamma(Z' \to l^+l^-)$ and $\Gamma_{Z'}$ being the partial lepton and total widths of the $Z'$ boson.

In the calculation of the total width $\Gamma_{Z'}$ we included the following channels: $Z' \to ff$, $W^+W^-$, and $ZH$ [4], where $H$ is the SM Higgs boson and $f$ are the SM fermions ($f = l, \nu, q$). The total width $\Gamma_{Z'}$ of the $Z'$ boson can be written as follows:

$$\Gamma_{Z'} = \sum_f \Gamma_{Z'}^{ff} + \Gamma_{Z'}^{WW} + \Gamma_{Z'}^{ZH}. \quad (13)$$

The presence of the two last decay channels, which are often neglected, is due to $Z-Z'$ mixing. However for large $Z'$ masses there is an enhancement that cancels the suppression due to tiny $Z-Z'$ mixing [3]. The ratio $\Gamma_{Z'}/M_{Z'}$ is pretty constant over the whole range of masses of interest, and is around $2\%$ for representative $Z'$ models originated from $E_6$ GUT and LR scenarios. Notice that for all $M_{Z'}$ values of interest for LHC the width of the $Z'$ boson should be considerably smaller than the mass window $\Delta M_{ll}$ in order to meet the narrow width approximation (NWA) condition.

In early study [15], to gain some approximate understanding of the acceptances for signal and background at different values of the invariant mass $M_{ll}$ of the $l^+l^-$ pair
and $Z'$ mass, we performed a simple study as follows. To estimate the $2\sigma$ constraints on the $Z'$ parameters at the LHC, we compared the events due to a $Z'$ signal to the events from the SM background in a 3% interval around the relevant values of the dilepton $l^+l^-$ invariant mass. This should be compatible with the expected energy resolution and with the fact that $\Gamma_{Z'}/M_{Z'} < 3\%$. We then required the signal events to be at least a $2\sigma$ fluctuation over the expected background, and in any case more than 3. This rough statistical analysis, as a preliminary stage, was enough to get an approximate answer to the questions we wanted to address.

Here, we are making a more careful analysis, employing the most recent measurements of dilepton processes provided by the experimental collaboration ATLAS, which have control on all the information needed to perform it in a more accurate way. In particular, for Abelian $Z'$ we compute the LHC $Z'$ production cross-section multiplied by the branching ratio into two leptons $l^+l^-$, $\sigma(pp \rightarrow Z') \cdot B(Z' \rightarrow l^+l^-)$, as a function of three free parameters $(a, v_e, v_u)$ at given $Z'$ mass $M_{Z'}$, and compare it with the limits of $\sigma_{95\% \text{C.L.}} \cdot B$ obtained from ATLAS data.

Our strategy in the present analysis is to use the SM backgrounds that have been carefully evaluated by the experimental collaboration and we simulate only the $Z'$ signal. Fig. 1 shows the observed and expected 95% C.L. upper limits on the production cross section times the branching fraction for $Z' \rightarrow l^+l^-$ as a function of $Z'$ mass, $M_{Z'}$. The data analyzed comprises $pp$ collisions at $\sqrt{s} = 13$ TeV, recorded by the ATLAS (36.1 fb$^{-1}$) detector at the LHC. The inner (green) and outer (yellow) bands around the expected limits represent $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties, respectively. Also shown are theoretical production cross sections $\sigma(pp \rightarrow Z') \cdot B(Z' \rightarrow l^+l^-)$ for Abelian $Z'$ and some representative models ($Z'_x$, $Z'_y$ and $Z'_{SSM}$) are calculated with FeynArts and FormCalc [22] for $K$-factor of 1.3. Notice, that the allowed (excluded) signature space for Abelian $Z'$ lies below (above) the upper limit $\sigma_{95\% \text{C.L.}} \cdot B$. The former ones are presented as vertical lines for three representative values $M_{Z'} = 2$, 3, and 4 TeV.

This procedure gives the upper constraints on the $Z'$ couplings. As mentioned above, due to the relations $\Gamma_{Z'} = \Gamma_{Z'} + X$ can be expressed through $a$, $v_e$, $v_u$ couplings only. Hence any constraints on the $Z'$ production cross section at a given $M_{Z'}$ yield the corresponding constraints on these couplings. In Fig. 2 we displays in 3-dim parameter space $(a, v_e, v_u)$ upper model-independent bounds at 95% C.L. on $M_{Z'}$ parameters obtained from equation $\sigma(pp \rightarrow Z') \cdot B(Z' \rightarrow l^+l^-) = \sigma_{95\% \text{C.L.}} \cdot B$ at $M_{Z'} = 3$ TeV. In Fig. 1 we also show the planar regions that are obtained by projecting onto the 2-dim planes the 95% C.L. allowed three-dimensional surface.

The Fig. 4 shows the exclusion contours at 95% C.L. in the $(a, v_e)$ parameter space, derived from the cross-section limits for three sample $Z'$ masses 2 TeV, 3 TeV and 4 TeV. The region inside each ellipse indicates the part of the parameter space in which the ratio of the resonance total width $\Gamma_{Z'}$ to its mass $M_{Z'}$ is below 1% (or 3%), which is comparable to the experimental mass resolution. Parameters for the benchmark models ($Z'_x$ and $Z'_{LR}$) are also shown by the the model marks (circle, rhombus, square, and triangle). The solid lines bounding the allowed areas indicated by color represent the boundaries of the regions excluded by this search for different $Z'$ masses (the region outside these lines is excluded). Points inside the ellipse, but where the absolute values of the $a$ and $v_e$ parameters are larger than at the exclusion contour, are considered to be excluded at a C.L. greater than 95%. Fig. 3 and Fig. 5 show similar exclusion contours at 95% C.L. in the $(a, v_u)$ and $(v_e, v_u)$ parameter space, respectively.

### IV. DISCUSSION AND CONCLUDING REMARKS

In one of our previous work [16], we carried out the model-independent analysis of $Z'$ effects in its indirect search at the LHC. It means that we supposed that the $Z'$ has a mass beyond the LHC reach. In such an approach, the $Z - Z'$ interference terms (which are proportional to the quadratic $Z'$ couplings) dominate in the $Z'$ production cross section $\sigma_{Z'}$. Besides, in this case the $Z'$ decay width $\Gamma_{Z'}$ is almost unimportant in the analysis of indirect (interference) $Z'$ effects. The indirect search allowed us to establish the maximum likeli-
FIG. 2. 95% C.L. allowed three-dimensional surface for Abelian $Z'$ with $M_{Z'} = 3 \text{ TeV}$ obtained from the comparison of the theoretical cross section $\sigma(pp \to Z') \cdot B(Z' \to l^+l^-)$ vs $\sigma_{95\%CL} \cdot B$ from dilepton production ATLAS data. Also, the condition $\Gamma_{Z'}/M_{Z'} < 0.01\%$ was taken into account. Two-dimensional projections of allowed region are also shown.

FIG. 3. The 95% C.L. allowed areas in the $(a, v_e)$ parameter space, derived from the cross-section limits for three sample $Z'$ masses 2 TeV, 3 TeV and 4 TeV. The hyperbolic regions correspond to the condition of $\Gamma_{Z'}/M_{Z'} < 0.01$ and $< 0.03$. Parameters for the representative models are also shown.

Nevertheless, we cannot put any definite assumptions on $M_{Z'}$ until the $Z'$ is detected explicitly. Thus the direct $Z'$ search must be also performed as well as the indirect one. Within the direct search concept we believe each time that the energy of the experiment is close to the $Z'$ mass. Hence the $Z - Z'$ interference terms turn out to be suppressed in the cross section while the pure $Z'$ production part (proportional to the quartic $Z'$ couplings) dominates. What about $\Gamma_{Z'}$, its value becomes crucial for the direct search. It is often believed that we deal with a narrow peak, $\Gamma_{Z'}/M_{Z'} \leq 0.01 - 0.03$.

The present paper is based on the ATLAS data on the Drell-Yan production at $\sqrt{s} = 13 \text{ TeV}$. The upper constraints on the $Z'$ couplings were obtained as a result of applying two conditions. The first one is a comparison of resonant production cross section with 95% C.L. upper limits $\sigma_{95\%CL} \cdot B$. The second condition is associated with NWA. We performed the analysis of direct $Z'$ search allowing to vary $M_{Z'}$ within the interval $1.25 \text{ TeV} < M_{Z'} < 4.5 \text{ TeV}$ and obtained that $|\tilde{a}|_{max} \sim 10^{-6}$, $|\tilde{a}v_e|_{max} \sim 10^{-6} - 10^{-5}$, $|\tilde{a}v_u|_{max} \sim 10^{-6}$.

Let us compare these results with some ones known from the literature ([15], [7], [8]). At first, they almost coincide with the $Z'$ constraints derived from the LHC data analysis at 8 TeV ([15]). Also, using (9) and $|\tilde{a}|_{max}$ from the Table I it is possible to calculate the upper limit for the $Z - Z'$ mixing angle. It is estimated as $|\theta_0| < 10^{-4} - 10^{-3}$ for the considered mass range $2 \text{ TeV} < M_{Z'} < 4 \text{ TeV}$. This evaluations are consistent with the results obtained from the global LEP data analysis ([22] and with direct $Z'$ search in the diboson channel at the LHC at 13 TeV ([7], [8]).
TABLE I. Model-independent upper limits at 95% C.L. on fermion couplings based on ATLAS dilepton production data in direct $Z'$ search at 13 TeV

| $M_{Z'}$ | 2 TeV | 3 TeV | 4 TeV |
|---------|-------|-------|-------|
| $|a|$ | 0.20  | 0.35  | 0.35  |
| $|\bar{a}|$ | 0.003 | 0.002 | 0.002 |
| $|v_e|$ | 1     | 1.1   | 1.1   |
| $|\bar{v}_e|$ | 0.01  | 0.007 | 0.005 |
| $|v_u|$ | 0.8   | 0.9   | 0.9   |
| $|\bar{v}_u|$ | 0.01  | 0.007 | 0.005 |

In conclusion, we studied Abelian $Z'$ bosons, whose phenomenology is controlled by only the $Z'$ mass and three fermion coupling constants. We estimated the LHC discovery potential with Run 2 data comprised of 36.1 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV and recorded by ATLAS detector at the CERN LHC. In particular, the model independent limits on the $Z'$ fermion couplings were obtained for the first time for representative $Z'$ signal mass points of $M_{Z'} = 2$, 3, and 4 TeV by using the ATLAS data collected at the LHC.

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