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# Anomalously interacting extra neutral bosons

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**Summary.** — We study phenomenological consequences of the Standard Model extension by the new spin-1 chiral fields with the internal quantum numbers of the electroweak Higgs doublets. There are at least three different classes of theories, all motivated by the hierarchy problem, which predict new vector weak-doublets with masses not far from the electroweak scale. We discuss resonance production of these neutral chiral $Z^*$ bosons at hadron colliders. The bosons can be observed as a Breit-Wigner resonance peak in the invariant dilepton mass distributions in the same way as the well-known extra gauge $Z'$ bosons. This includes them into a list of very interesting objects for early searches with the first LHC data. Moreover, the $Z^*$ bosons have unique signatures in transverse momentum, angular and pseudorapidity distributions of the final leptons, which allow to distinguish them from the other heavy neutral resonances.

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PACS 13.85.Fb – Inelastic scattering: two-particle final states.
PACS 14.70.Pw – Other gauge bosons.

## 1. – Introduction

The method of the covariant derivatives leads to the unique minimal form of the gauge bosons couplings to the fermions. Although the gauge symmetry allows anomalous interactions in the initial Lagrangian, all known fundamental spin-1 bosons, photon, $W^{\pm}$, $Z$ and gluons, possess only renormalizable minimal interactions with the known fermions. The anomalous interactions are considered as effective ones. They are generated on the level of the quantum loop corrections. Usually they are proportional to the additional square of a small coupling constant and can be neglected in the first-order approximation.

A different picture is realized at the low energy QCD domain, where gluon and quark degrees of freedom are substituted by physical hadronic states. The latter can be described by an effective field theory. For example, spin-1 boson states, associated with

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the vector fields, interact with baryons in all possible ways. So, due to strong dynamics, the vector $\rho$ meson has both, comparable by the magnitude, minimal and anomalous couplings with $\bar{\psi}\gamma^\mu\psi$ and $\partial_\nu(\bar{\psi}\sigma^{\mu\nu}\psi)$ currents, respectively [1]. Both currents have the same quantum numbers $J^{PC} = 1^{--}$ and since the parity and charge conjugation are conserved in QCD they define the quantum numbers of the meson.

The axial-vector meson $a_1$ has different quantum numbers $1^{++}$, which allow it also to have both a minimal interaction with $\bar{\psi}\gamma^\mu\gamma^5\psi$ current and an anomalous interaction with $\partial^\mu(\bar{\psi}\gamma^5\psi)$ current. But the most interesting is another axial-vector meson $b_1$ with the quantum numbers $1^{+-}$. Due to the latter the meson has only anomalous interaction with the tensor current $\partial_\nu(\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi)$. In fact, this QCD feature can be applied to the electroweak physics as well. We will see how it plays a key role below.

Let us assume that the electroweak gauge sector of the Standard Model (SM) is extended by a doublet of new spin-1 *chiral* bosons $\boldsymbol{W}^*_\mu$ with the internal quantum numbers of the SM Higgs boson. They can originate, for example, from the extensions of the SM such as Gauge-Higgs unification, larger gauge groups [2] or technicolor models. However, due to the lack of fully realistic models, the collider expectations for signals from these chiral bosons have not yet been studied in details. Nevertheless, it is possible to point out several model-independent and unique signatures, which allow to identify the production of such bosons at the hadron colliders [3].

Since the tensor current mixes the left-handed and the right-handed fermions, which in the SM are assigned to the different representations, the gauge doublet should have only anomalous interactions:

$$(1)\quad \mathcal{L}^* = \frac{g}{M}\left(\partial_\mu W^{*-}_\nu \quad \partial_\mu \overline{W}^{*0}_\nu\right)\cdot \overline{D_R}\,\sigma^{\mu\nu}\begin{pmatrix} U_L \\ D_L \end{pmatrix} + \frac{g}{M}\left(\overline{U_L} \quad \overline{D_L}\,\right)\sigma^{\mu\nu} D_R \cdot \begin{pmatrix} \partial_\mu W^{*+}_\nu \\ \partial_\mu W^{*0}_\nu \end{pmatrix},$$

where $M$ is the boson mass, $g$ is the coupling constant of the $SU(2)_W$ weak gauge group, and $U$ and $D$ generically denote up-type and down-type leptons and quarks(1). The bosons, coupled to the tensor quark currents, are some types of *excited* states as far as the only orbital angular momentum with $L = 1$ contributes to the total angular moment, while the total spin of the system is zero. This property manifests itself in their derivative couplings to fermions and in the different chiral structure of the interactions in contrast to the minimal gauge interactions.

For simplicity in (1) we have introduced only interactions with the down-type right-handed singlets, $D_R$. The coupling constant is chosen in such a way that in the Born approximation all partial fermionic decay widths of the well-known hypothetical $W'$ boson with the SM-like interactions

$$(2)\qquad \mathcal{L}'_{CC} = \frac{g}{\sqrt{2}}\,W'^-_\mu \cdot \overline{D_L}\gamma^\mu U_L + \frac{g}{\sqrt{2}}\,\overline{U_L}\gamma^\mu D_L \cdot W'^+_\mu$$

and the charged $W^{*\pm}$ boson with the same mass are identical.

In the same way as in many of the SM extensions several Higgs doublets are introduced the realistic model could include several gauge doublets. Using the charge-conjugated

(1) Here we assume also universality of lepton and quark couplings with different flavors.

doublet

$$\boldsymbol{W}_\mu^{*\,\mathrm{c}} = \begin{pmatrix} \overline{W}_\mu^{*0} \\ -W_\mu^{*-} \end{pmatrix} \tag{3}$$

(or new ones with the hypercharges opposite to the $\boldsymbol{W}_\mu^*$ doublet) it is possible to construct more complicated models including up-type right-handed singlets, $U_R$, as well.

## 2. – The model

The minimal set of the chiral heavy bosons in the proposed extension of the SM consists of the four spin-1 particles: the two charged $W^{*\pm}$ states and the two neutral $CP$-even $Z^* = (W^{*0} + \overline{W}^{*0})/\sqrt{2}$ and $CP$-odd $\widetilde{Z}^* = (W^{*0} - \overline{W}^{*0})/\sqrt{2}\,i$ combinations. The corresponding Lagrangian for the neutral states reads

$$\mathcal{L}^*_{\mathrm{NC}} = \frac{g}{\sqrt{2}M}\left(\bar{D}\sigma^{\mu\nu}D \cdot \partial_\mu Z^*_\nu + i\bar{D}\sigma^{\mu\nu}\gamma^5 D \cdot \partial_\mu \widetilde{Z}^*_\nu\right). \tag{4}$$

In the present paper we will discuss only the resonance production of the neutral heavy bosons and their subsequent decay into a pair of the light charged leptons. This process is the "golden channel" for early discovery at the hadron colliders. However, in this case it is impossible to discriminate the multiplicative quantum numbers of the neutral bosons, namely $P$ and $C$, due to their identical signatures. Therefore, in the following calculations we will consider only one of them, for instance, $Z^*$ boson.

In order to compare the experimentally accessible distributions between the tensor couplings and the vector ones, we introduce topologically analogous but minimal gauge interactions of the $Z'$ boson

$$\mathcal{L}'_{\mathrm{NC}} = \frac{g}{2}\,\bar{D}\gamma^\mu D \cdot Z'_\mu. \tag{5}$$

In the Born approximation eqs. (4) and (5) lead to the same cross-sections for the hadroproduction and decay of both neutral heavy bosons, $Z^*(\widetilde{Z}^*)$ and $Z'$, when they have the same mass. As we have assumed, the lepton and the quark couplings are characterized by the same coupling constant, $g$, of the $SU(2)_W$ weak gauge group. So, the leptonic branching ratio is $\mathcal{B}(Z^*/Z' \to \ell^+\ell^-) = 1/12 \approx 8\%$ and the total fermionic decay width

$$\Gamma = \frac{g^2}{4\pi}\,M \approx 0.034\,M \tag{6}$$

is around 3% of the mass of the resonance.

All calculations we carried out in the framework of the CompHEP package [4]. To this end a new model has been implemented, which includes additional new bosons and their corresponding interactions.

## 3. – Numerical simulations for neutral bosons

Up to now, the excess in the Drell-Yan process with high-energy invariant mass of the lepton pairs remains the clearest indication of a new heavy boson production at the

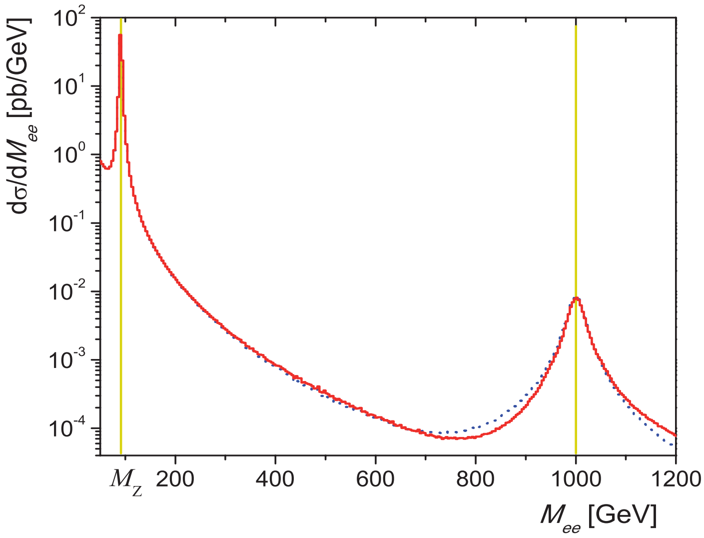


Fig. 1. – The invariant dilepton mass distributions for the $Z'$ boson (dotted) and the chiral excited $Z^*$ boson (solid) with the Drell-Yan SM background (from the photon and the $Z$ boson) at the LHC for $\sqrt{s} = 10\,\text{TeV}$.

hadron colliders on the early stage. Therefore, we will concentrate on the production and decay of the neutral bosons, where the full kinematics is experimentally reconstructible. In the following we will use the CompHEP package [4] for the numeric calculations of various distributions for the inclusive processes $pp \to \gamma/Z/Z^*/Z' \to \ell^+\ell^-$ with a CTEQ6L choice for the proton parton distribution set. For both final leptons we impose angular cuts relevant to the LHC detectors on the pseudorapidity range $|\eta_\ell| < 2.5$ and the transverse momentum cuts $p_T > 20\,\text{GeV}$.

Since the current direct constraints from the D0 and CDF Collaborations place a lower bound on the mass of new heavy neutral resonances decaying into light lepton pairs about 1 TeV, we set $M \geq 1\,\text{TeV}$. For the high dilepton masses the cross sections of the new boson productions with $M = 1\,\text{TeV}$ at the peaks are about two orders of magnitude higher than the corresponding Drell-Yan background (fig. 1). Therefore, the peak should be clearly visible.

For an estimation of the statistical significance of expected signal we can use the simplest "number counting" approach, which is based on the expected rate of events for the signal, $s$, and background processes, $b$. The significance can be calculated by the formula

$$S_{cL} = \sqrt{2\left((s+b)\ln\left(1+\frac{s}{b}\right) - s\right)} \tag{7}$$

according to the method presented in Appendix A of ref. [5], which follows directly from the Poisson distribution.

We will focus on the LHC reach with an integrated luminosity of up to $100\,\text{pb}^{-1}$ of data at $\sqrt{s} = 10\,\text{TeV}$. As far as the center-of-mass energy for the 2010–2011 runs is 7unTeV, at which the cross-sections are roughly two times lower, $200\,\text{pb}^{-1}$ of data will be equivalent to the first scenario. In order to estimate the discovery potential and the

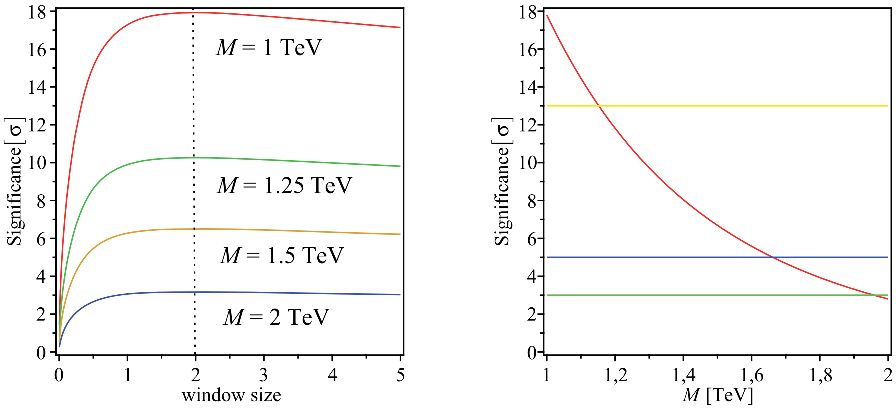


Fig. 2. – Left: the signal significance as a function of the window size is given for the different masses. Right: the $Z^*$ boson discovery potential at $\sqrt{s} = 10\,\text{TeV}$ for $100\,\text{pb}^{-1}$.

exclusion limit for the first LHC data, we need to generate several samples for different resonance masses. In the "number counting" approach, we simply count the expected number of events within some window under the resonance including the background. The optimal window size $[M - 2\Gamma, M + 2\Gamma]$ can be guessed from the left panel of fig. 2.

For different $Z^*$ masses the statistical significance of the expected signal can be evaluated using window size $\pm 2\Gamma$ around the resonance positions (the right panel of fig. 2). The lowest horizontal line in this plot corresponds to $3\,\sigma$ level and shows the evidence for discovery, which can be obtained for the resonance masses up to $2\,\text{TeV}$. The middle horizontal line shows the discovery potential at $5\,\sigma$ level for the masses of the chiral bosons up to $1.65\,\text{TeV}$.

The peaks in the invariant mass distributions originate from the Breit-Wigner propagator form, which is the same both for $Z'$ and $Z^*$ bosons in the leading Born approximation. Therefore, in order to discriminate them we need to investigate additional

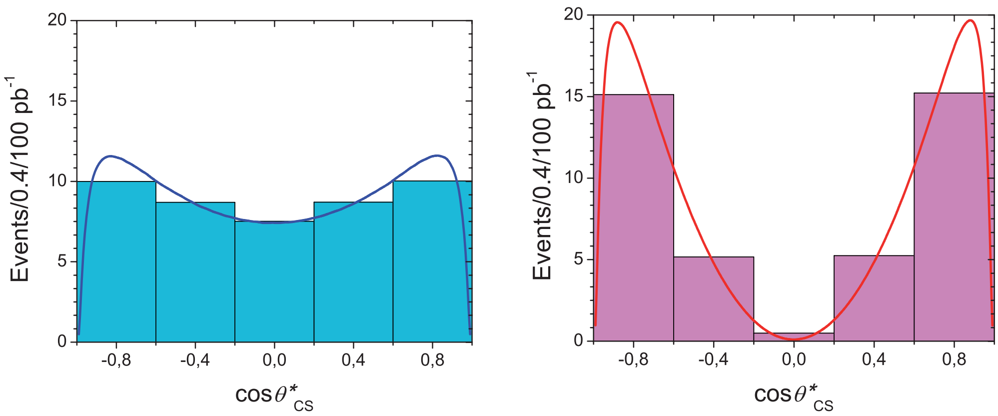


Fig. 3. – The differential distributions of the gauge $Z'$ boson (left) and the chiral excited $Z^*$ boson (right) as functions of $\cos\theta^*_{\text{CS}}$ for $M = 1\,\text{TeV}$.

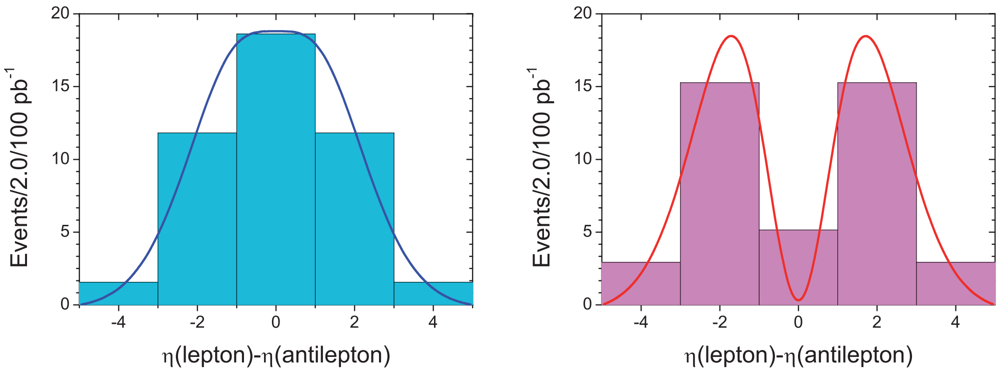


Fig. 4. – The differential distributions for the gauge $Z'$ boson (left) and the chiral excited $Z^*$ boson (right) as functions of the difference of the lepton pseudorapidities for $M = 1\,\text{TeV}$.

distributions selecting only "on-peak" events with the invariant dilepton masses in the chosen range $[M - 2\Gamma, M + 2\Gamma]$. According to paper [6] a crucial difference between the chiral bosons and other resonances should come from the analysis of the angular distribution of the final-state leptons with respect to the boost direction of the heavy boson in the rest frame of the latter (the Collins-Soper frame [7]) (fig. 3).

Indeed, the angular distribution for the $Z^*$ bosons will lead to the large negative value of the centre-edge asymmetry $A_{\text{CE}}$ [8],

$$\sigma A_{\text{CE}} = \int_{-\frac{1}{2}}^{+\frac{1}{2}} \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*_{\text{CS}}}\,\mathrm{d}\cos\theta^*_{\text{CS}} - \left[\int_{+\frac{1}{2}}^{+1} \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*_{\text{CS}}}\,\mathrm{d}\cos\theta^*_{\text{CS}} + \int_{-1}^{-\frac{1}{2}} \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*_{\text{CS}}}\,\mathrm{d}\cos\theta^*_{\text{CS}}\right], \tag{8}$$

while the distributions of other known resonances (even with different spins) possess positive or near to zero asymmetries. The corresponding calculations show that for resonance masses up to 1.15 TeV it is possible to disentangle between the most interesting cases of $Z^*$ and $Z'$ resonances (horizontal upper line in the right-hand plot of fig. 2). Another "unexpected" consequence of the new angular distribution is shown in fig. 4. Combining these distributions should allow to differentiate these bosons for higher resonance masses.

To estimate the exclusion limit for given statistics we will apply simple considerations. For example, if looking for an excess in the invariant dilepton mass distribution with chosen window above 1 TeV, we do not find any event (which is in agreement with the SM), then it is still allowed for 3 signal events to fluctuate down to 0 with a probability of 5%. It means that the resonances up to masses 1.65 TeV, which should give more than 3 events, will be excluded at 95% confidence level.

## 4. – Remarks on the charged bosons case

The cleanest method for discovery of the charged heavy bosons at the hadron colliders is the detection of their subsequent leptonic decays into isolated high transverse-momentum leptons without a prominent associated jet activity. In this case they can be

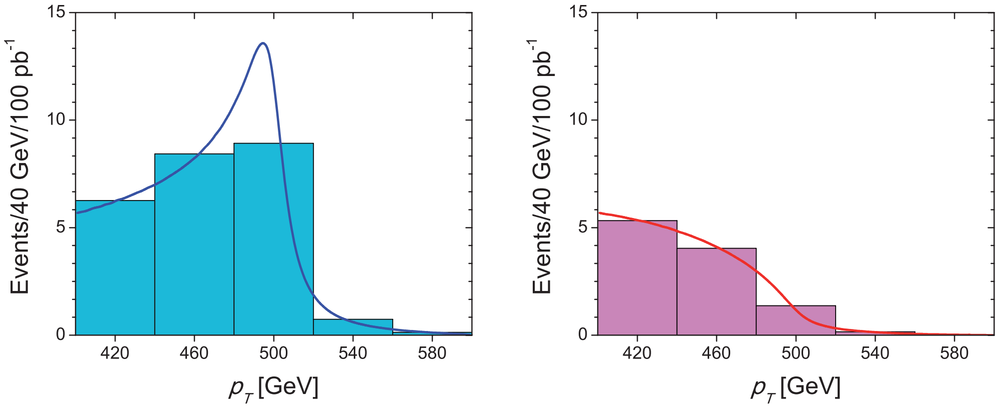


Fig. 5. – The differential distributions for the $Z'$ boson (left) and the chiral excited $Z^*$ boson (right) as functions of the lepton transverse momentum $p_{\mathrm{T}}$ for $M = 1\,\mathrm{TeV}$.

observed through the Jacobian peak in the transverse momentum distribution. It has become proverbial (see, for example, the textbook [9]) that the Jacobian peak is characteristic of all two-body decays. However, it is not the case for the decay of the new chiral bosons [10].

It has been found in [11] that tensor interactions lead to a new angular distribution of the outgoing fermions

$$\frac{\mathrm{d}\sigma(q\bar{q} \to Z^*/W^* \to f\bar{f})}{\mathrm{d}\cos\theta} \propto \cos^2\theta, \tag{9}$$

in comparison with the well-known vector interaction result

$$\frac{\mathrm{d}\sigma(q\bar{q} \to Z'/W' \to f\bar{f})}{\mathrm{d}\cos\theta} \propto 1 + \cos^2\theta. \tag{10}$$

It was realized later [10] that this property ensures a distinctive signature for the detection of the new interactions at the hadron colliders. At first sight, the small difference between the distributions (9) and (10) seems unimportant. However, the absence of the constant term in the first case results in new experimental signatures.

The angular distribution for vector interactions (10) includes a nonzero constant term, which leads to the kinematical singularity in $p_{\mathrm{T}}$ distribution of the final fermion

$$\frac{1}{\cos\theta} \propto \frac{1}{\sqrt{(M/2)^2 - p_T^2}} \tag{11}$$

in the narrow width approximation $\Gamma \ll M$

$$\frac{1}{(s - M^2)^2 + M^2\Gamma^2} \approx \frac{\pi}{M\Gamma}\delta(s - M^2). \tag{12}$$

This singularity is transformed into a well-known Jacobian peak due to a finite width of the resonance. In contrast to this, the pole in the decay distribution of the $Z^*/W^*$ bosons is canceled out and the fermion $p_T$ distribution even reaches zero at the kinematical endpoint $p_T = M/2$ (fig. 5).

The $Z^*/W^*$ boson decay distribution has a broad smooth hump with the maximum below the kinematical endpoint, instead of a sharp Jacobian peak. Therefore, in contrast to the usual procedure of the direct and precise determination of the resonance mass the new distribution does not allow to do it. Moreover, a relatively small decay width of the chiral bosons leads to a wide distribution, that obscures their identification as resonances at hadron colliders.

## 5. – Conclusions

In conclusion we would like to stress that the new type of spin-1 chiral bosons can exist. They are well motivated from the hierarchy problem point of view and are predicted by at least three different classes of theories that represent different approaches for explaining the relative lightness of the Higgs doublets. The decay distributions of the chiral bosons differ drastically from the distributions of the known gauge bosons. Therefore, the discovery of such type of distributions will point out to an existence of a compositeness, of a new symmetry and, even, of extra dimensions.

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